IEEE ITALY SECTION

2016 MEDICAL INFORMATICS ISMISS

September, 13th - 17th 2016

Biblioteca Comunale "Giovanni Bovio"

Trani, Puglia, Italy

Wearable body tracking for Occupational Biomechanics and Telemedicine

Emanuele Ruffaldi

PERCRO Lab, TeCiP Institute

Scuola Superiore Sant'Anna

Overview

- Virtual Ergonomics
- Occupational Biomechanics
- Inertial Assessment
  - Bayesian
  - AHRS
- Combined motion and effort
- Additional Uses
- Conclusions

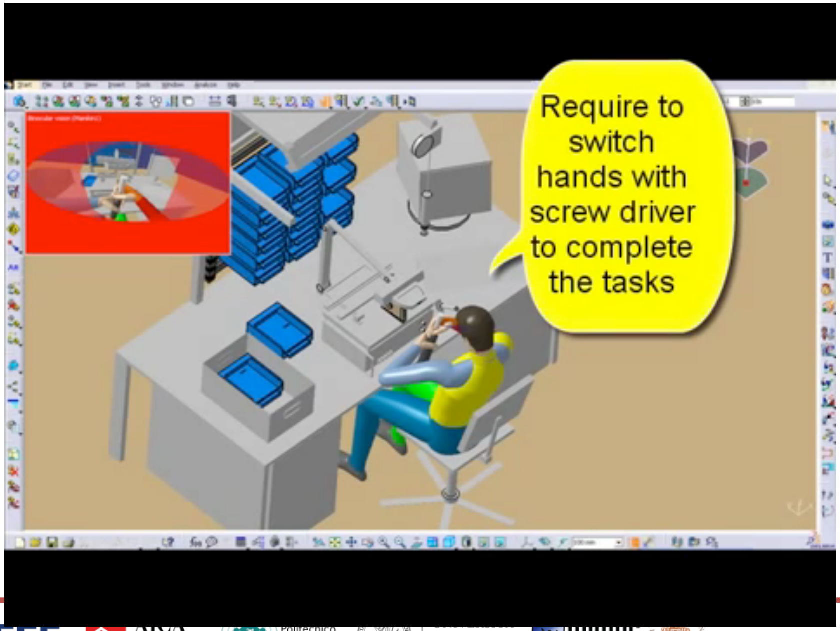
Modeling for Virtual Ergonomics

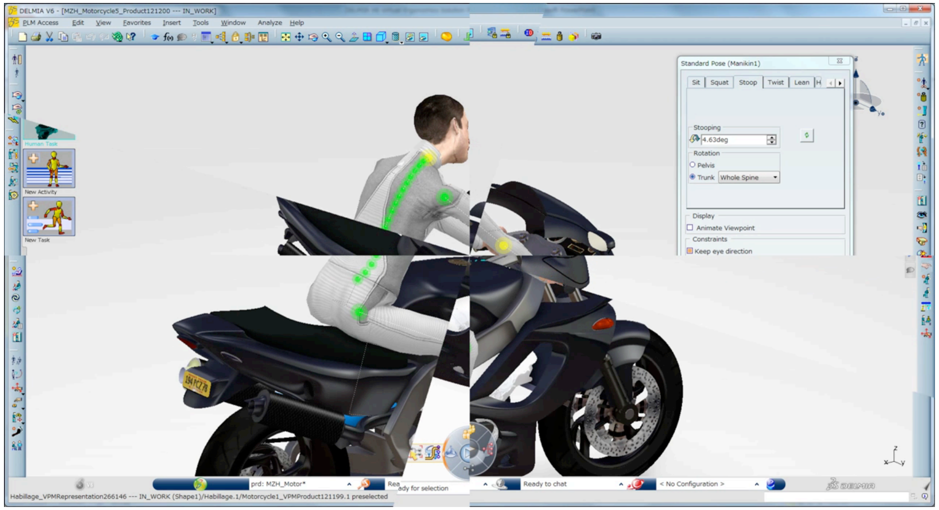
The simulation of human task in a Virtual Environment with virtual estimates of the ergonomic effects

Uses

Biomechanical Models

Simulated Actions





Dassault Systems Virtual Ergonomics

Virtual Reality Ergonomic Testing

Virtual Reality for Ergonomics allows a real person to experience a task or a work situation

Advantages

- Controlled environment for the execution
- Monitoring of multiple body variables
- Experimentation of variation

Advancements in Virtual Reality technology allows for reducing the gap between the real task

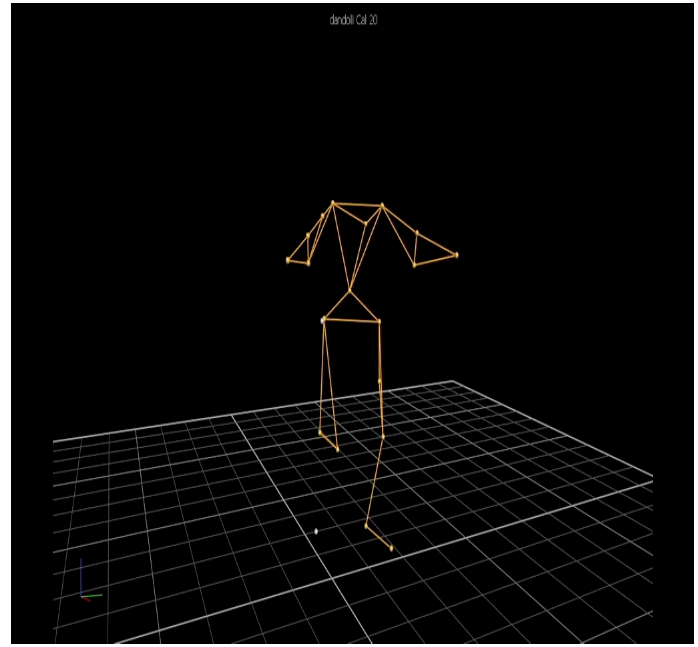
- Improved visual quality and usability of VR devices
- Improvements of simulations

FORD, 2012

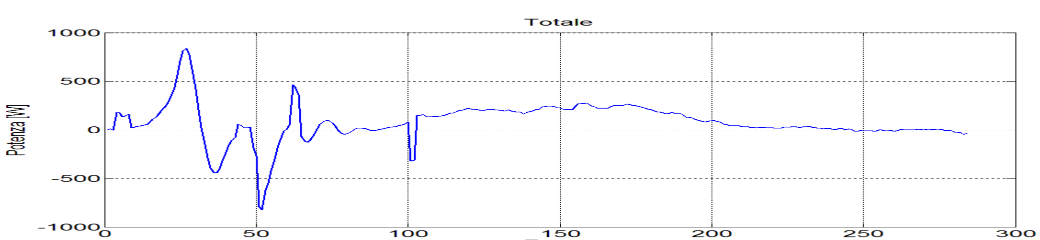
Occupational Biomechanics

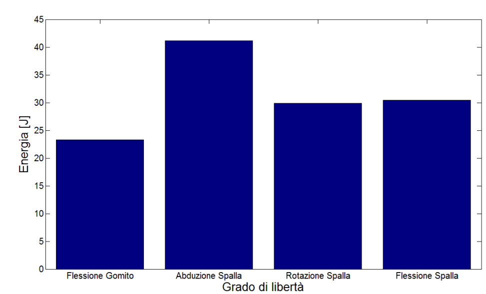
"Occupational biomechanics is the study of movement related to the act of performing occupational duties. Each job requires different physical demands, so the realm of occupational biomechanics is of a broad nature"

OB also for System Design



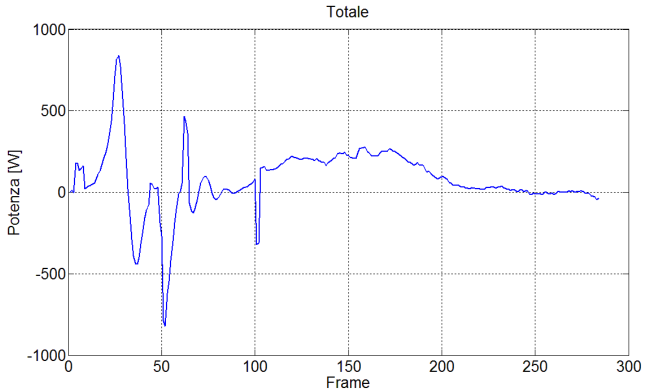
Analysis of torque, velocity, power and energy by task





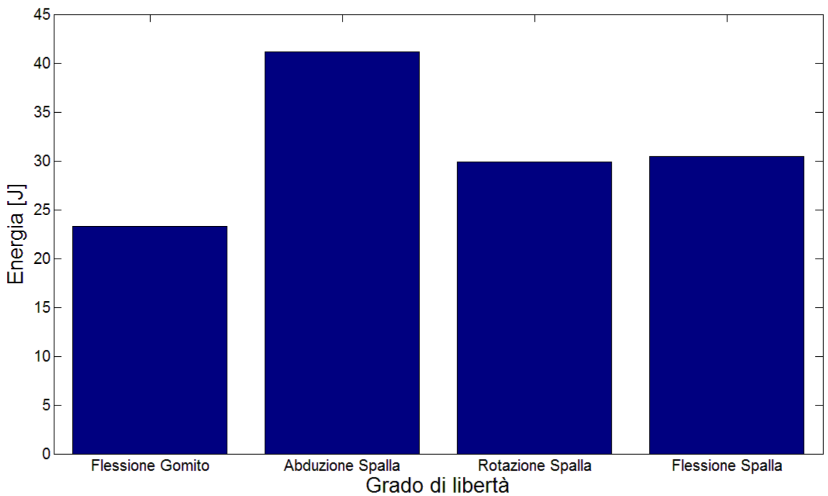
[Filippeschi]

OB also for System Design



Analysis of torque, velocity,

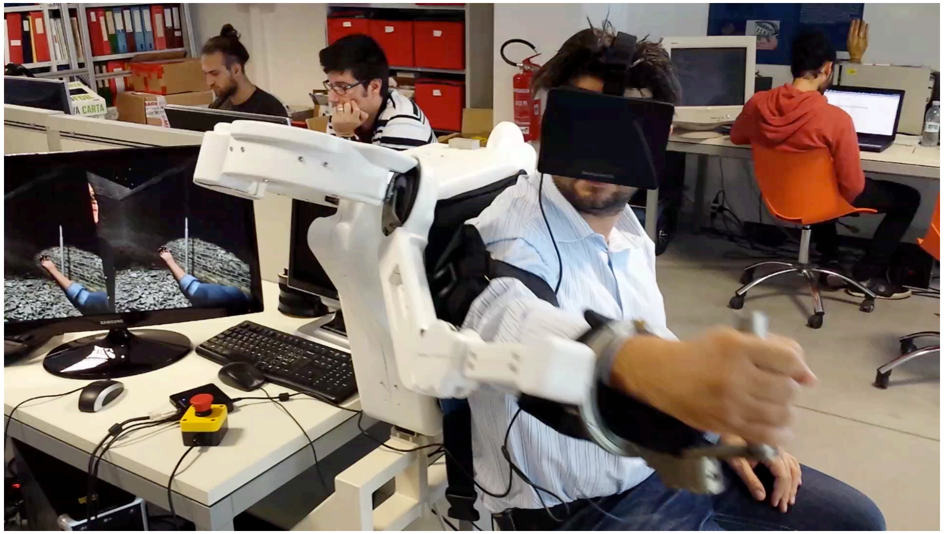
power and energy by task



Results for System Design

- CAD simulation of the motion
- Estimation of joint ranges for the exoskeleton
- Estimation of the torques and power for the joints

[ALEX – KineteK SSSA Spinoff]



[Ruffaldi, EH 2014]

WMSD

- Work-related Musculo Skeletal Disorders (WMSD) are the third main reason for disability and early retirement in the U.S.
- In Italy it has been estimated a 159.7% increment in WMSD reports from 2006 to 2009-2010.
- According to this data it is clear how important is correctly diagnosing this kind of pathologies.

Traditional Assessment

- Observational techniques (Standard Assessment)
  - Visual inspection
  - Subjective evaluation
- Objective measurements
  - Motion Capture
  - Force exertion (pressure sensors/surface EMG)
  - Combination of the two
  - Standard assessment Vs Ad-hoc assessment

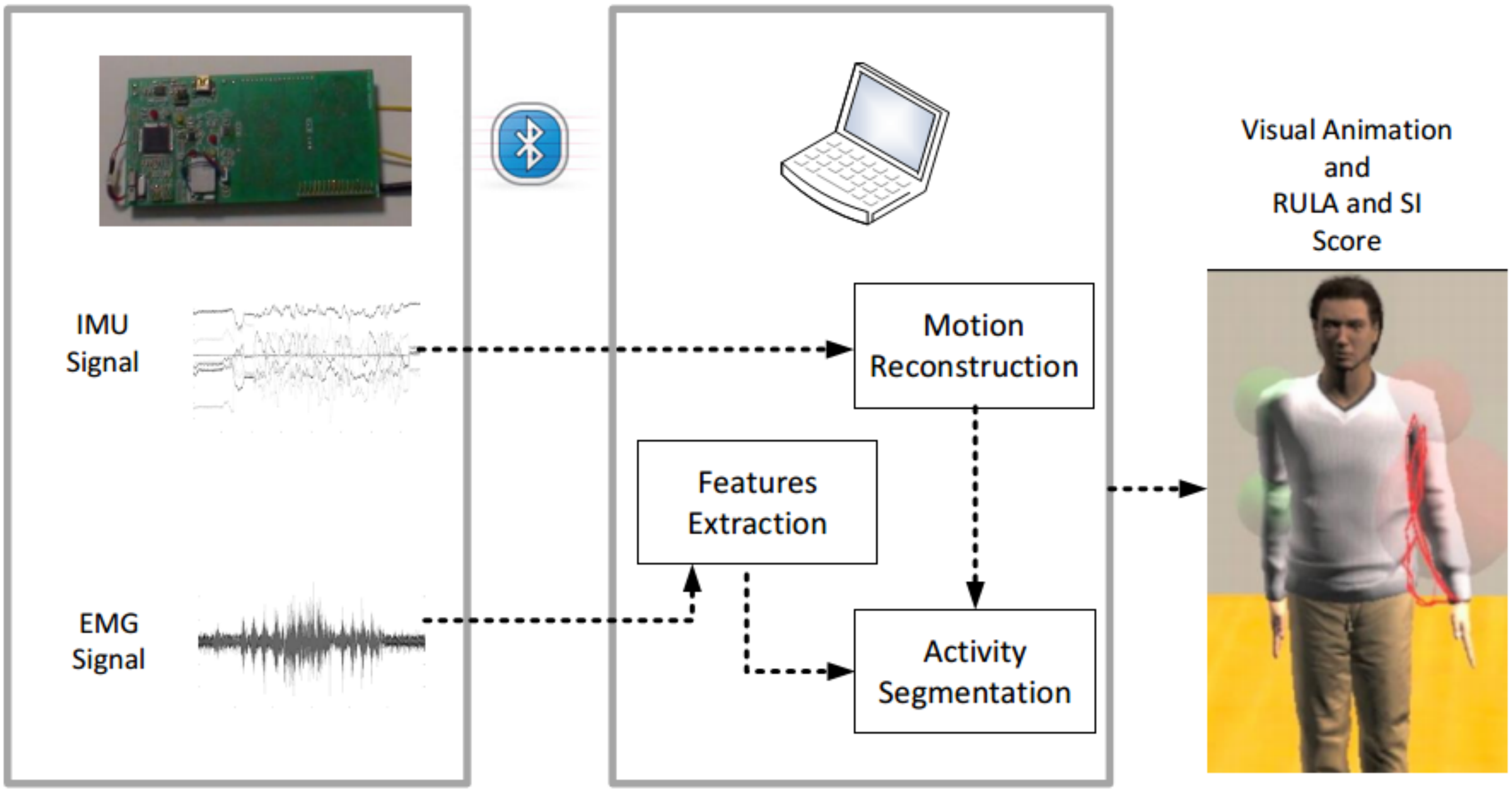
ERGANE-SMOOTI System

System developed by SSSA

Peppoloni L., Filippeschi A. & Ruffaldi E. (2014). Assessment of task ergonomics with an upper limb wearable device. In Control and Automation (MED), 2014 22nd Mediterranean Conference of (pp. 340-345). . doi:10.1109/MED.2014.6961394

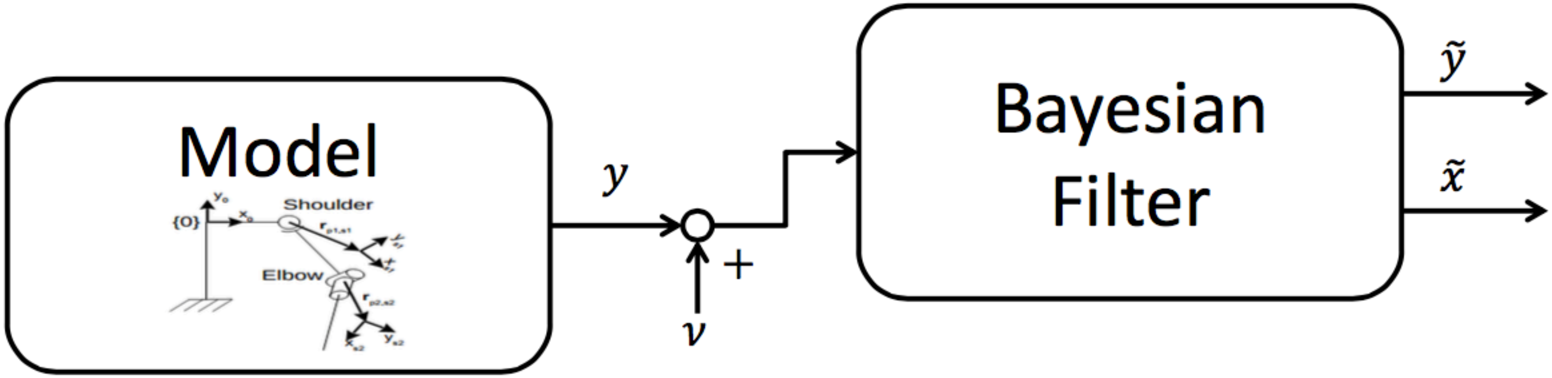
Avizzano C.A., Ruffaldi E. & Bergamasco M. (2014). A novel wearable biometric capture system. In Control and Automation (MED), 2014 22nd Mediterranean Conference of (pp. 351-355). . doi:10.1109/MED.2014.6961396

Architecture

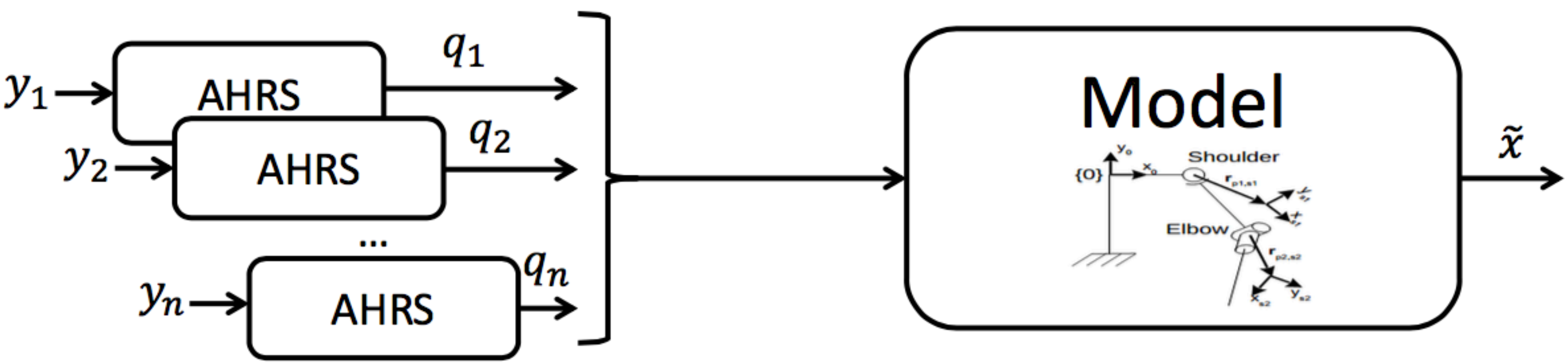


Inertial Body Tracking

- Bayesian Filtering Approach

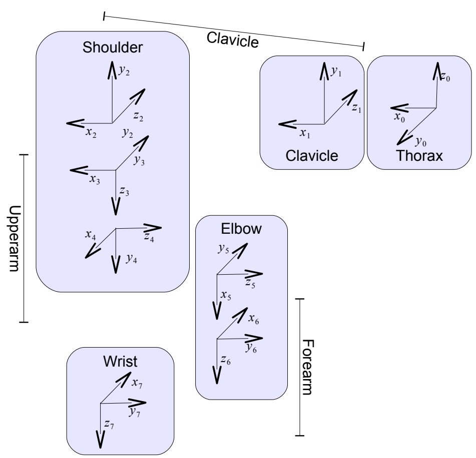


- Independent Estimation



Biomechanical Model

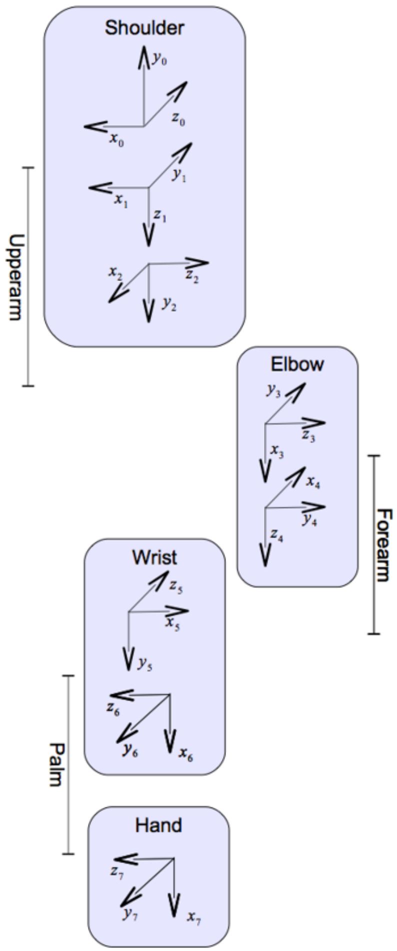
- Choose the model depending on the target application: Clavicle, Shoulder, Elbow, Wrist
- 7-DOF Model for Clavicle-Wrist
  - Modeled as D-H



Frame	a_i	α_i	d_i	ϑ_i	**Joint**
1	0	$\pi/2$	0	ϑ_1	Scapula Protraction
2	l_{cl}	$\pi/2$	0	ϑ_2	Scapula Elevation
3	0	$\pi/2$	0	ϑ_3	Shoulder Abduction
4	0	$\pi/2$	0	$\vartheta_4 - \pi/2$	Shoulder Rotation
5	l_{ua}	0	0	$\vartheta_5 + \pi/2$	Shoulder Flexion
6	0	$\pi/2$	0	$\vartheta_6 + \pi/2$	Elbow Flexion
7	0	0	l_{fa}	ϑ_7	Elbow Rotation

See Also: ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand

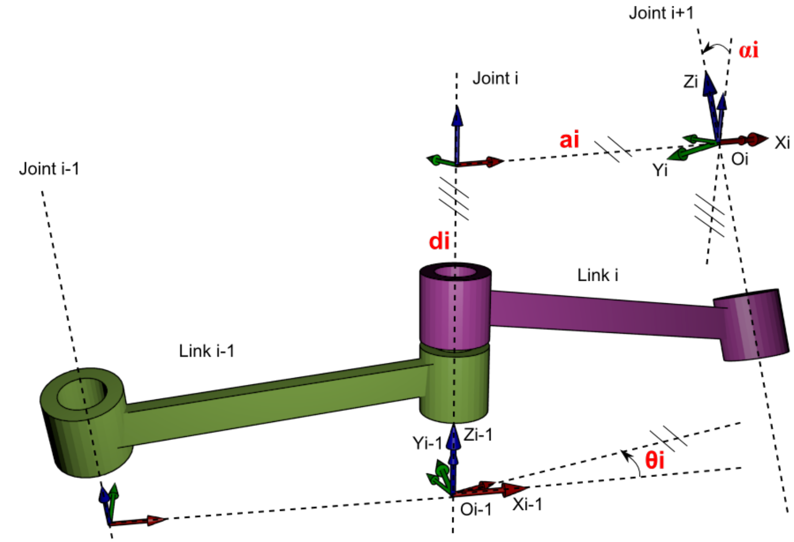
Other Model



- 7 DoFs rigid bodies kinematic chain
  - Rooted in the chest
  - Shoulder abduction-adduction
  - Shoulder rotation
  - Shoulder flexion-extension
  - Elbow flexion-extension
  - Forearm pronation-supination
  - Wrist flexion – extension
  - Wrist abduction – adduction
- IMUs associated to s# frames
  - Rigid transformation from parent link to sensor frame

Denavit-Hartenberg

- Convention used in Robotics
- Using 4 parameters



$$ {}^{n-1}T_n = \mathrm{Trans}_{z_{n-1}}(d_n) \cdot \mathrm{Rot}_{z_{n-1}}(\theta_n) \cdot \mathrm{Trans}_{x_n}(r_n) \cdot \mathrm{Rot}_{x_n}(\alpha_n) $$

$$ {}^{n-1}T_n = \left[\begin{array}{ccc|c} \cos\theta_n & -\sin\theta_n\cos\alpha_n & \sin\theta_n\sin\alpha_n & r_n\cos\theta_n \\ \sin\theta_n & \cos\theta_n\cos\alpha_n & -\cos\theta_n\sin\alpha_n & r_n\sin\theta_n \\ 0 & \sin\alpha_n & \cos\alpha_n & d_n \\ \hline 0 & 0 & 0 & 1 \end{array}\right] = \left[\begin{array}{ccc|c} & R & & T \\ \hline 0 & 0 & 0 & 1 \end{array}\right] $$

Dynamical System Formulation

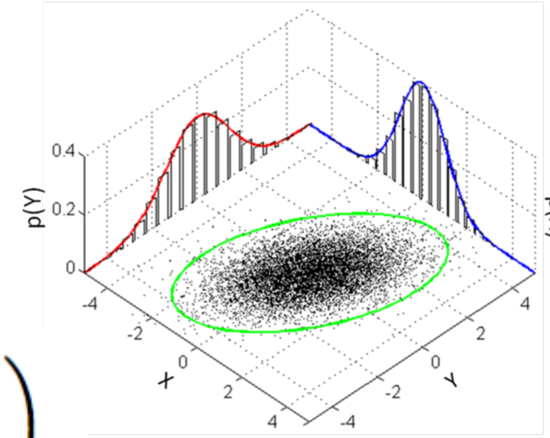
- Not necessarily a Linear relationship between state (x) and output (y)

$$x(k+1) = f(x(k)) + \nu_k$$

$$y(k) = h(x(k)) + \epsilon_k$$

- When linear functions Kalman Filter is optimal
- When non-linear it is possible to approximate the function

Multivariate-Normals



- PD $\mathbf{x} \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$

$$f_{\mathbf{x}}(x_1, \ldots, x_k) = \frac{1}{\sqrt{(2\pi)^k |\boldsymbol{\Sigma}|}} \exp\left(-\frac{1}{2}(\mathbf{x}-\boldsymbol{\mu})^{\mathrm{T}} \boldsymbol{\Sigma}^{-1}(\mathbf{x}-\boldsymbol{\mu})\right)$$

- Partitioned MVN

$$\Sigma = \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{XY}^T & \Sigma_{YY} \end{pmatrix}$$

- Marginalization
- Conditioning on y

$$\mu' = \mu_X + \Sigma_{XY}\Sigma_{YY}^{-1}(y - \mu_Y)$$

$$\Sigma' = \Sigma_{XX} - \Sigma_{XY}\Sigma_{YY}^{-1}\Sigma_{XY}^T$$

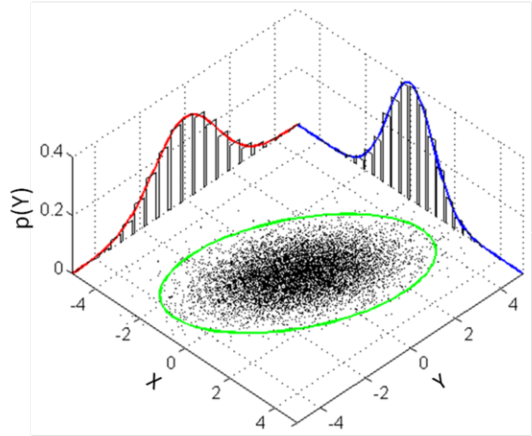
- Linear Transformation

$$N(y|Ax + b, R)$$

$$\Sigma_z = \begin{pmatrix} P & PA^T \\ AP & R + APA^T \end{pmatrix}$$

$$\mu_z = \begin{pmatrix} \mu \\ A\mu + b \end{pmatrix}$$

Multivariate-Normals



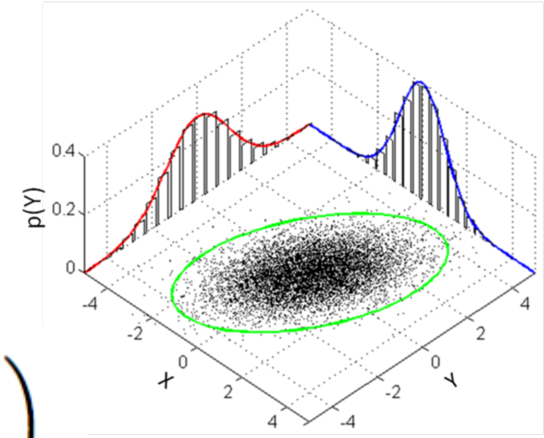
- PD $\mathbf{x} \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$

$$f_{\mathbf{x}}(x_1, \ldots, x_k) = \frac{1}{\sqrt{(2\pi)^k |\boldsymbol{\Sigma}|}} \exp\left(-\frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^{\mathrm{T}} \boldsymbol{\Sigma}^{-1} (\mathbf{x} - \boldsymbol{\mu})\right)$$

Multivariate-Normals

- PD $\mathbf{x} \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$

$$f_{\mathbf{x}}(x_1, \ldots, x_k) = \frac{1}{\sqrt{(2\pi)^k |\boldsymbol{\Sigma}|}} \exp\left(-\frac{1}{2}(\mathbf{x}-\boldsymbol{\mu})^{\mathrm{T}} \boldsymbol{\Sigma}^{-1} (\mathbf{x}-\boldsymbol{\mu})\right)$$

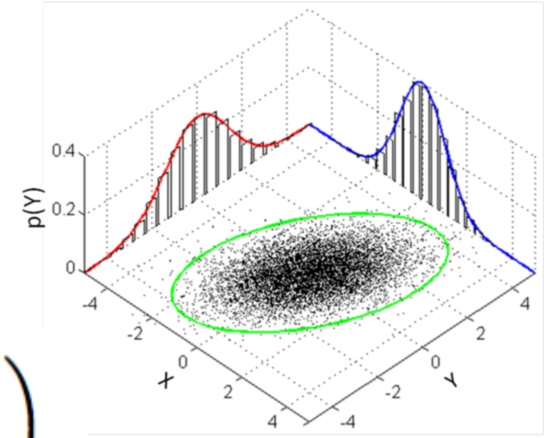


- Partitioned MVN

$$\Sigma = \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{XY}^T & \Sigma_{YY} \end{pmatrix}$$

- Marginalization

Multivariate-Normals



- PD $\mathbf{x} \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$

$$f_{\mathbf{x}}(x_1,\ldots,x_k) = \frac{1}{\sqrt{(2\pi)^k|\boldsymbol{\Sigma}|}} \exp\left(-\frac{1}{2}(\mathbf{x}-\boldsymbol{\mu})^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}(\mathbf{x}-\boldsymbol{\mu})\right)$$

- Partitioned MVN

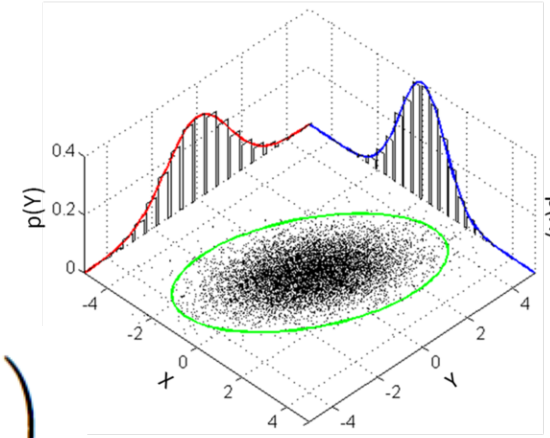
$$\Sigma = \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{XY}^T & \Sigma_{YY} \end{pmatrix}$$

- Marginalization
- Conditioning on y

$$\mu' = \mu_X + \Sigma_{XY}\Sigma_{YY}^{-1}(y - \mu_Y)$$

$$\Sigma' = \Sigma_{XX} - \Sigma_{XY}\Sigma_{YY}^{-1}\Sigma_{XY}^T$$

Multivariate-Normals



- PD $\mathbf{x} \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$

$$f_{\mathbf{x}}(x_1, \ldots, x_k) = \frac{1}{\sqrt{(2\pi)^k |\boldsymbol{\Sigma}|}} \exp\left(-\frac{1}{2}(\mathbf{x}-\boldsymbol{\mu})^{\mathrm{T}} \boldsymbol{\Sigma}^{-1} (\mathbf{x}-\boldsymbol{\mu})\right)$$

- Partitioned MVN

$$\Sigma = \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{XY}^T & \Sigma_{YY} \end{pmatrix}$$

- Marginalization
- Conditioning on y

$$\mu' = \mu_X + \Sigma_{XY}\Sigma_{YY}^{-1}(y - \mu_Y)$$

$$\Sigma' = \Sigma_{XX} - \Sigma_{XY}\Sigma_{YY}^{-1}\Sigma_{XY}^T$$

- Linear Transformation

$$N(y|Ax + b, R)$$

$$\Sigma_z = \begin{pmatrix} P & PA^T \\ AP & R + APA^T \end{pmatrix}$$

$$\mu_z = \begin{pmatrix} \mu \\ A\mu + b \end{pmatrix}$$

Kalman as MVN

- We can solve easily the Kalman Filtering and generalize it using the MVN formulation
- We have

$$\mathbf{x}_k = \mathbf{F}_k \mathbf{x}_{k-1} + \mathbf{B}_k \mathbf{u}_k + \mathbf{w}_k$$

$$\mathbf{w}_k \sim \mathcal{N}(0, \mathbf{Q}_k)$$

$$\mathbf{z}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{v}_k$$

$$\mathbf{v}_k \sim \mathcal{N}(0, \mathbf{R}_k)$$

- The observation of z means that we condition a MVN and indeed the above condition formula is the same Kalman filtering

Kalman State Equations

$$x_i = \left[\vartheta_i, \dot{\vartheta}_i, \ddot{\vartheta}_i\right]^T \qquad i = 1, \ldots, 7$$

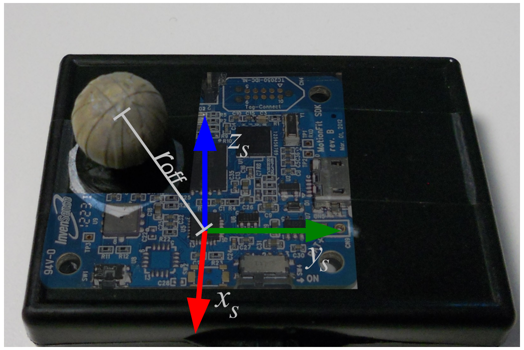
$$\vartheta_i(k+1) = \vartheta_i(k) + T_s\dot{\vartheta}_i(k) + \tfrac{1}{2}T_s^2(\ddot{\vartheta}_i(k) + \nu_k)$$
$$\dot{\vartheta}_i(k+1) = \dot{\vartheta}_i(k) + T_s(\ddot{\vartheta}_i(k) + \nu_k)$$
$$\ddot{\vartheta}_i(k+1) = \ddot{\vartheta}_i(k) + \nu_k$$

$$A_i = \begin{bmatrix} 1 & T_s & \frac{T_s^2}{2} \\ 0 & 1 & T_s \\ 0 & 0 & 1 \end{bmatrix} \quad Q_i = \begin{bmatrix} \frac{T_s^2}{2} \\ T_s \\ 1 \end{bmatrix} \begin{bmatrix} \frac{T_s^2}{2} & T_s & 1 \end{bmatrix}$$

In this model the acceleration is subject to random walk

Inertial Observations

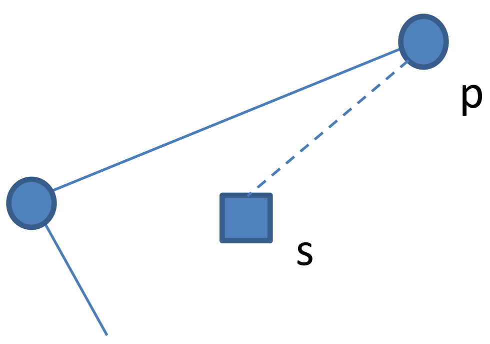
- 9-DOF IMU
- Acceleration (gravity direction)
  - Gravity Normalized $[m/s^2 10^-3]$
- Angular Velocity (local rate)
  - Rad/s
- Magnetometer (magnetic North)
  - Tesla $[\mu T]$



Kalman Observation Equations

$$\omega_s^s = R_p^s(\omega_p^p + \dot{\vartheta}_{p+1} z_0)$$
$$\ddot{x}_s^s = R_p^s \ddot{x}_p^p + S(\dot{\omega}_s^s) r_{p,s}^s + S(\omega_s^s)^2 r_{p,s}^s + R_0^s g^0$$
$$m_s^s = R_0^s m^0$$

These equations come from the Joint Kinematics in Newton-Euler formulation.
S(omega) is the skew matrix



$$T_i^{i-1} = \begin{bmatrix} R_i^{i-1} & r_i^{i-1} \\ \mathbf{0}_{1,3} & 1 \end{bmatrix} = \begin{bmatrix} c_{\vartheta i} & -s_{\vartheta i} c_{\alpha i} & s_{\vartheta i} s_{\alpha i} & a_i c_{\vartheta i} \\ s_{\vartheta i} & c_{\vartheta i} c_{\alpha i} & -c_{\vartheta i} s_{\alpha i} & a_i s_{\vartheta i} \\ 0 & s_{\alpha i} & c_{\alpha i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

D-H parametrization

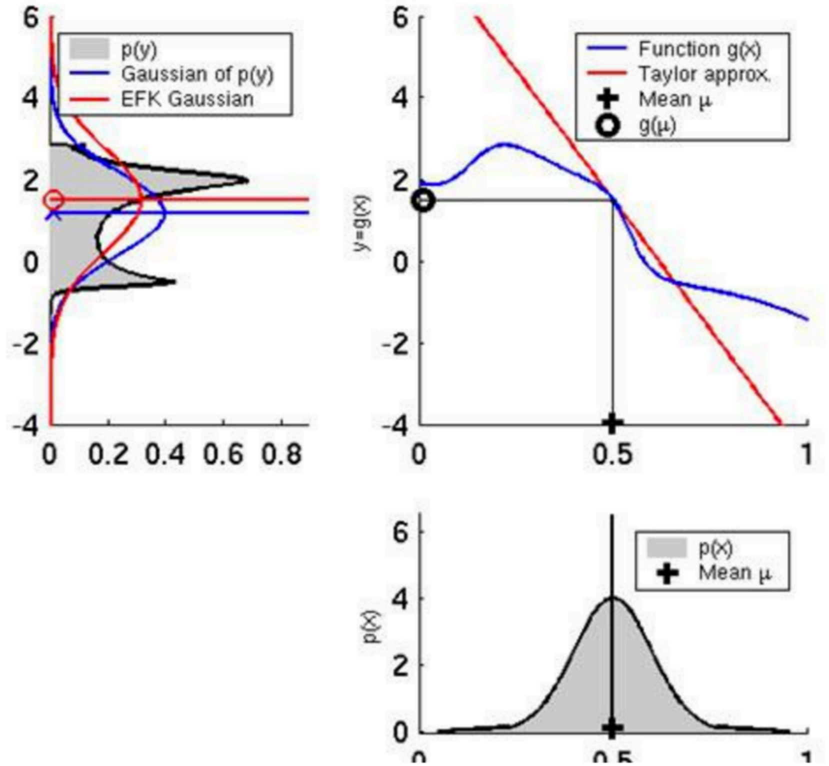
[Peppoloni, 2013, SISY]

EKF and UKF

- Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) are two ways for solving a tracking problem with non-linear function
  - EKF is a first order approximation at a point
  - UKF is a second order approximation of the Taylor expansion via sampling of a Gaussian Distribution
- Particle systems are not suitable because the dimension of the state-space is high

EKF

- The function is linearized by taking the derivative (Jacobian) at the current position



[Thrun 2002]

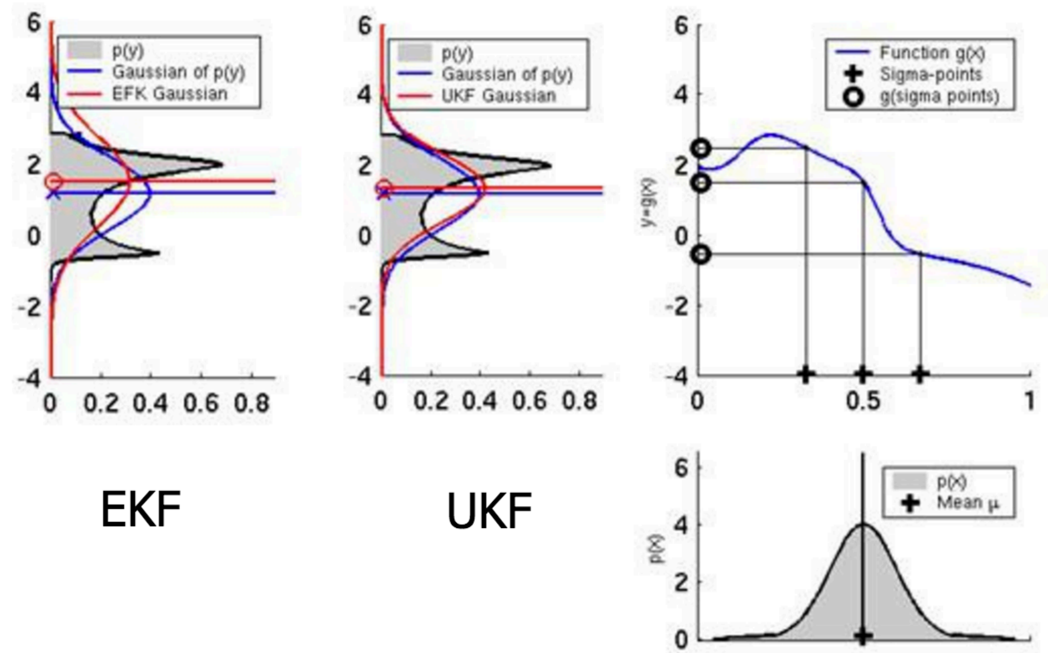
UKF Formulation

- The key element of the UKF is the unscented transformation that allows the generalized transformation of a Multivariate Gaussian

1. Sample the Gaussian in 2n+1 with n the dimensions (called sigma points)
2. Compute the non linear function f for every sigma point
3. Rebuild the resulting Gaussian

UKF

- The Gaussian is approximated by taking samples over the MVN, transforming them and then rebuilding a new Gaussian



[Thrun 2002]

UKF Sampling

- Points

$$\mathbf{x}^{(0)} = \mathbf{m}$$
$$\mathbf{x}^{(i)} = \mathbf{m} + \left[\sqrt{(n+\lambda)\,\mathbf{P}}\right]_i, \quad i = 1, \ldots, n$$
$$\mathbf{x}^{(i)} = \mathbf{m} - \left[\sqrt{(n+\lambda)\,\mathbf{P}}\right]_i, \quad i = n+1, \ldots, 2n$$

- The sqrt of a matrix is such that
  - A = sqrt(P)
  - P = A A’
- Typically A is the Cholesky decomposition of the matrix

UKF Combination

- After the evaluation of the points we can perform

$$\boldsymbol{\mu}_U \approx \sum_{i=0}^{2n} W_m^{(i)} \mathbf{y}^{(i)}$$

$$\mathbf{S}_U \approx \sum_{i=0}^{2n} W_c^{(i)} (\mathbf{y}^{(i)} - \boldsymbol{\mu}_U)(\mathbf{y}^{(i)} - \boldsymbol{\mu}_U)^T$$

$$\mathbf{C}_U \approx \sum_{i=0}^{2n} W_c^{(i)} (\mathbf{x}^{(i)} - \mathbf{m})(\mathbf{y}^{(i)} - \boldsymbol{\mu}_U)^T$$

- Weights are

$$W_m^{(0)} = \lambda/(n+\lambda)$$
$$W_c^{(0)} = \lambda/(n+\lambda) + (1 - \alpha^2 + \beta)$$
$$W_m^{(i)} = 1/\{2(n+\lambda)\}, \quad i = 1, \ldots, 2n$$
$$W_c^{(i)} = 1/\{2(n+\lambda)\}, \quad i = 1, \ldots, 2n.$$

$$\lambda = \alpha^2 (n + \kappa) - n.$$

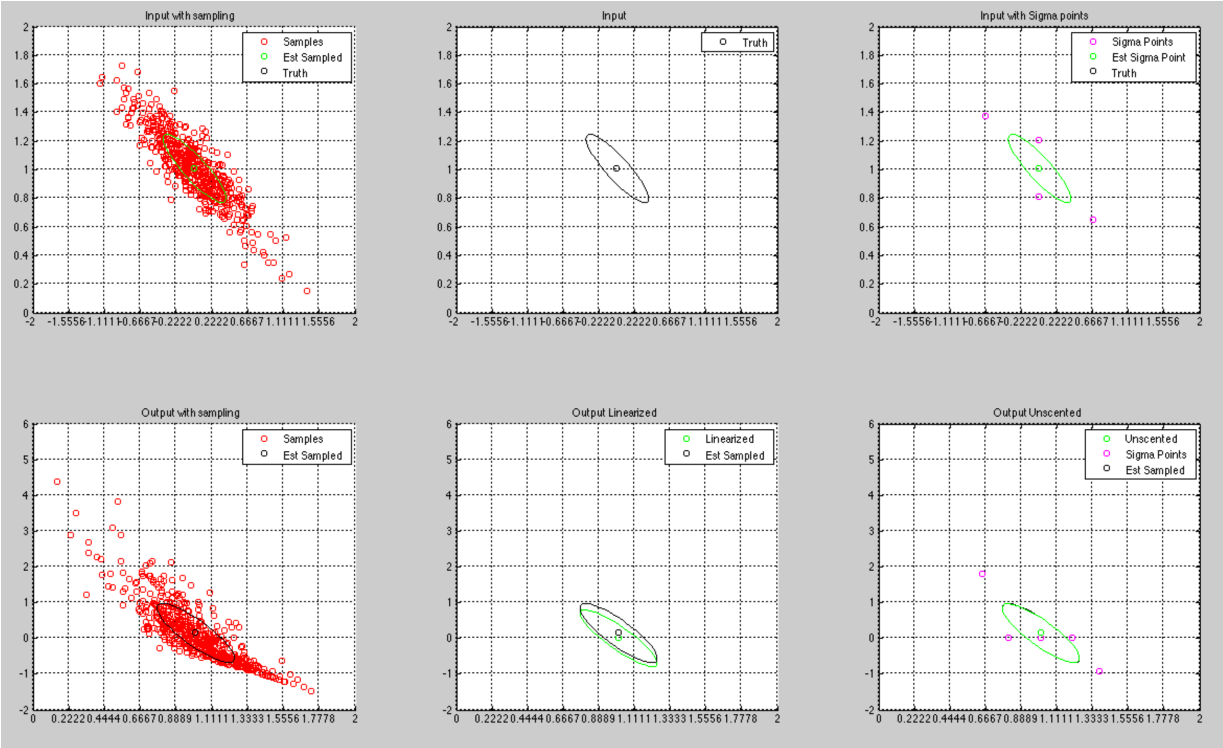
UKF Matrix Form

- It is possible to adopt a matrix form

$$
\begin{aligned}
\mathbf{X} &= \begin{bmatrix} \mathbf{m} & \cdots & \mathbf{m} \end{bmatrix} + \sqrt{c} \begin{bmatrix} \mathbf{0} & \sqrt{\mathbf{P}} & -\sqrt{\mathbf{P}} \end{bmatrix} \\
\mathbf{Y} &= \mathbf{g}(\mathbf{X}) \\
\boldsymbol{\mu}_U &= \mathbf{Y}\,\mathbf{w}_m \\
\mathbf{S}_U &= \mathbf{Y}\,\mathbf{W}\,\mathbf{Y}^T \\
\mathbf{C}_U &= \mathbf{X}\,\mathbf{W}\,\mathbf{Y}^T,
\end{aligned}
$$

Unscented Example

- Take the functions [x2, 2 x1 (x2+x1)] not really un-linear
- Compare the first-order approximation with Unscented and Montecarlo sampling



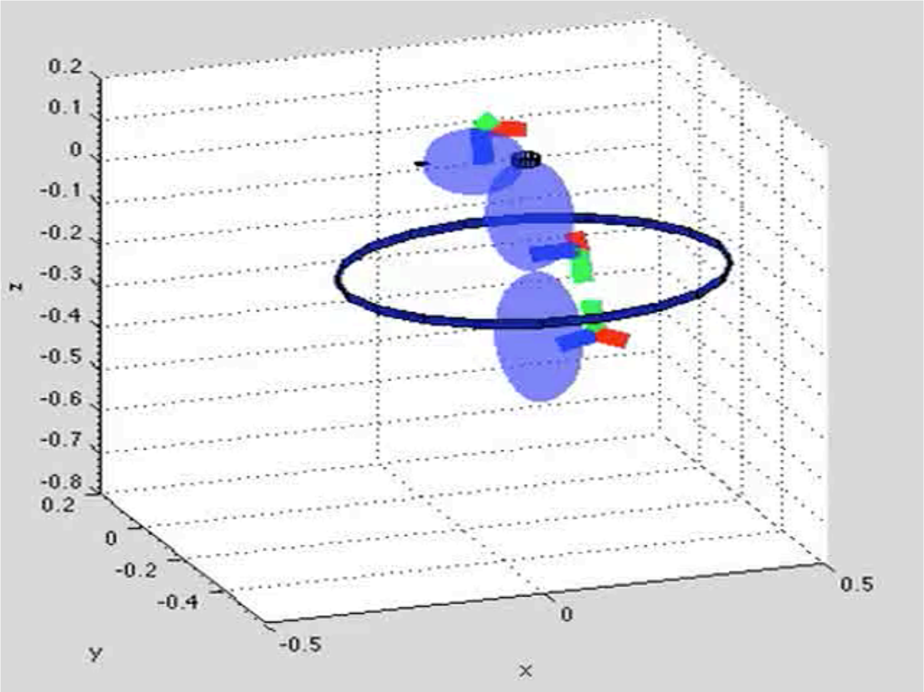
Code: https://github.com/eruffaldi/compare-mvn-transform

Model Validation

- Two fold validation using joints angles and body landmark positions (RMSE/Cross-Correlation):
  - Shoulder
  - Elbow
  - IMUs positions

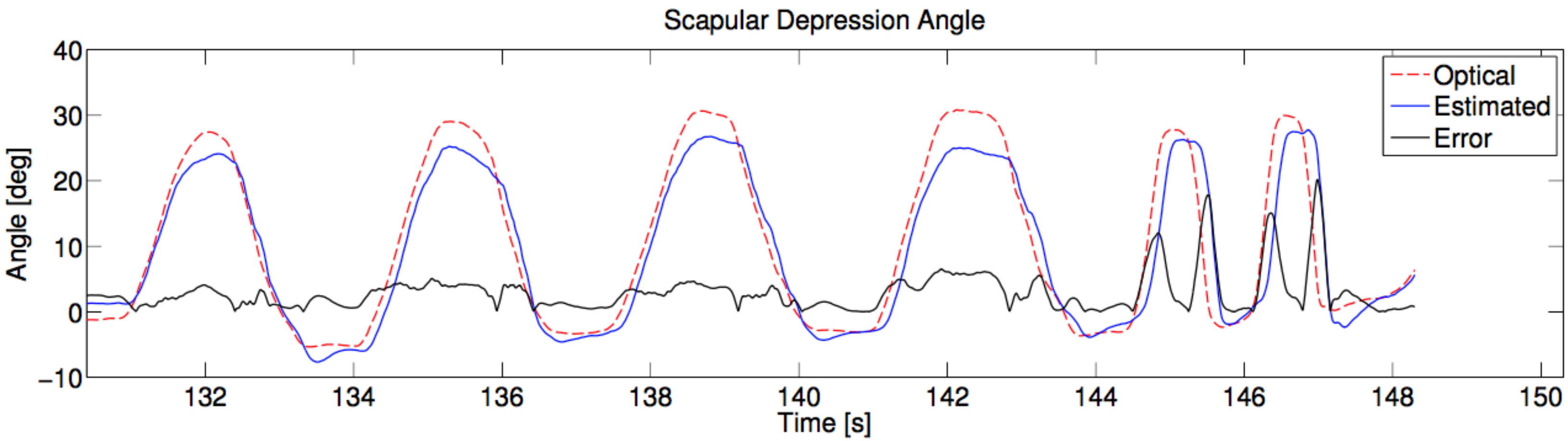
- 1. Against optical ground truth (Vicon, Mx+ 20, 7 cameras, 100 Hz)
- 2. Against SoA 5 DoF model
- One subject performing functional movements to explore the possible joints workspace
- All the algorithms were implemented in Matlab/Simulink (100 Hz)

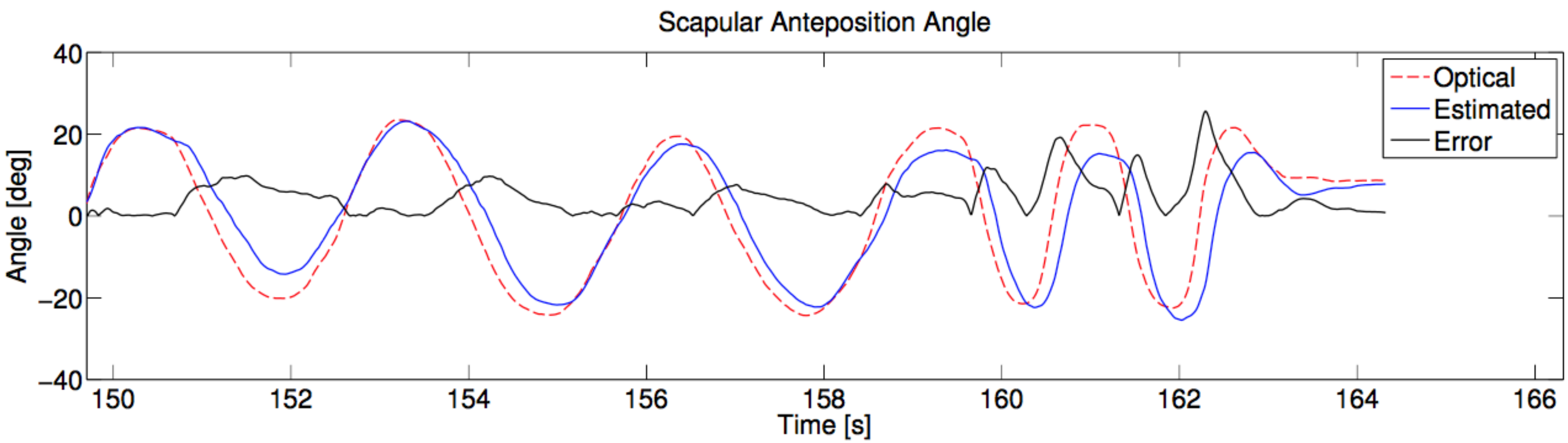
Result



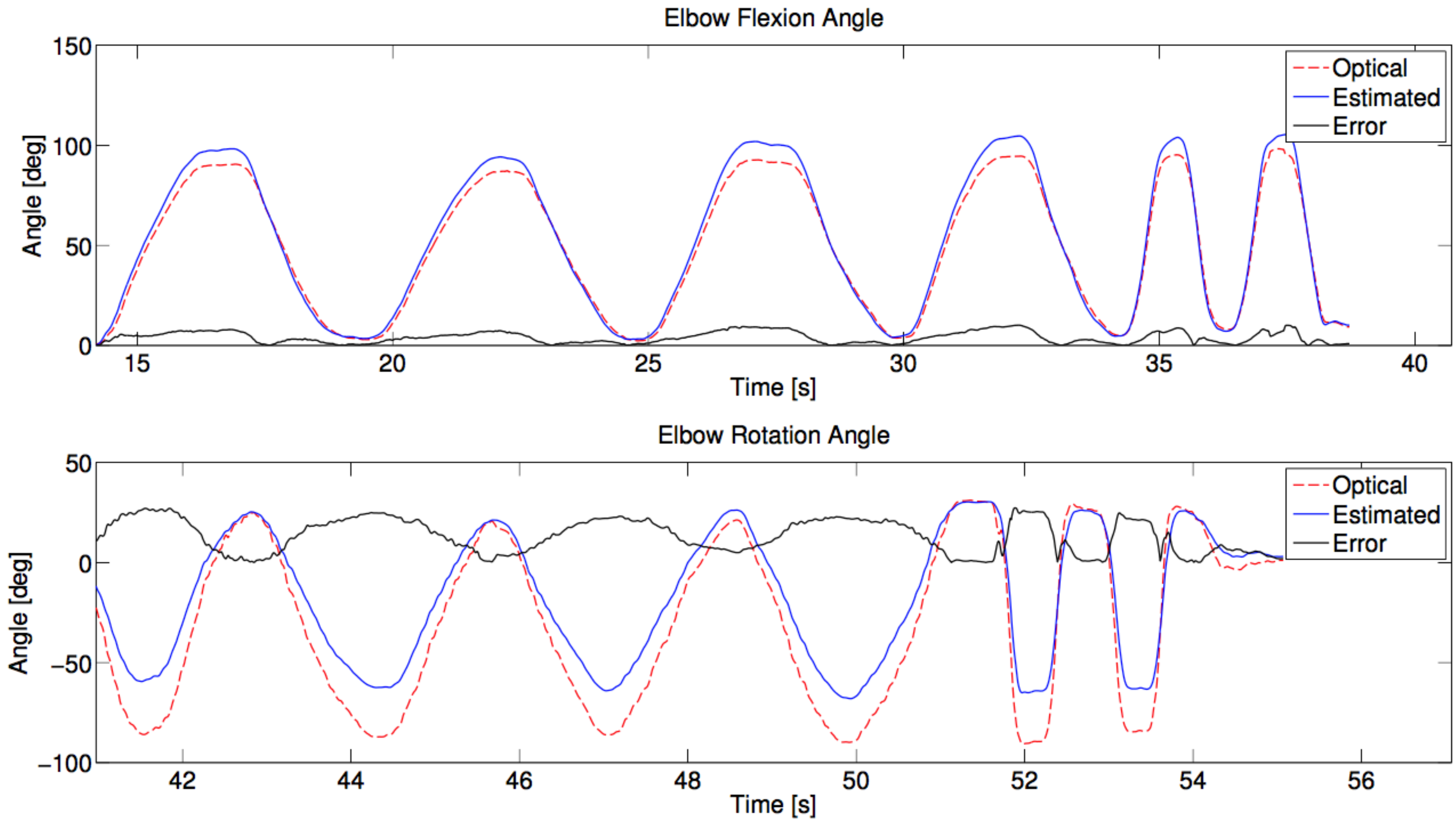
- Peppoloni L., Filippeschi A., **Ruffaldi E.** & Avizzano C.A. (2013). A novel 7 degrees of freedom model for upper limb kinematic reconstruction based on wearable sensors. In*Intelligent Systems and Informatics (SISY), 2013 IEEE 11th International Symposium on* (pp. 105-110). . doi:10.1109/SISY.2013.6662551

Joint Angles



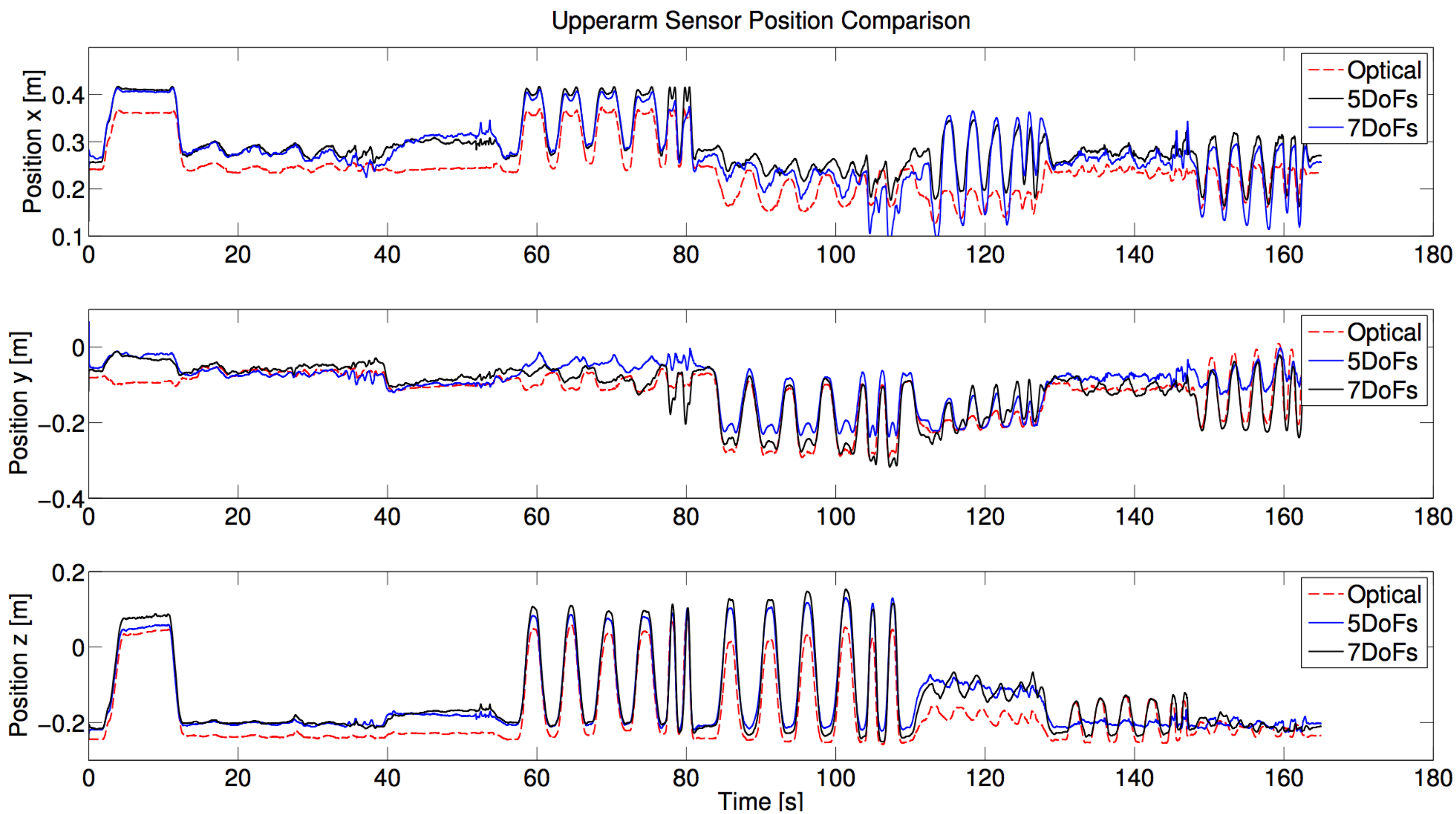


Joints

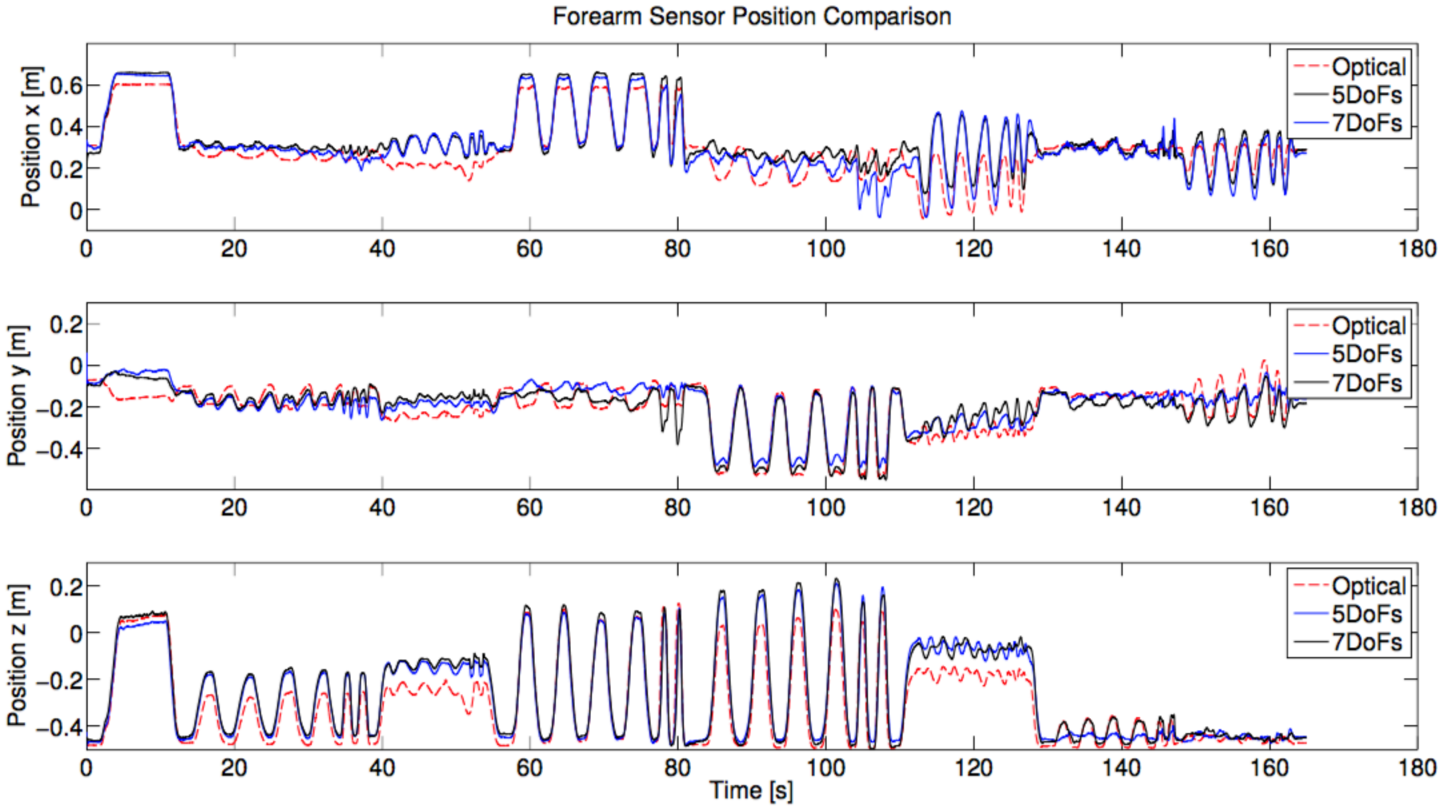


Elbow Flexion Angle
Angle [deg]
Time [s]
Optical
Estimated
Error
150
100
50
0
15
20
25
30
35
40
Elbow Rotation Angle
Angle [deg]
Time [s]
Optical
Estimated
Error
50
0
−50
−100
42
44
46
48
50
52
54
56

Position

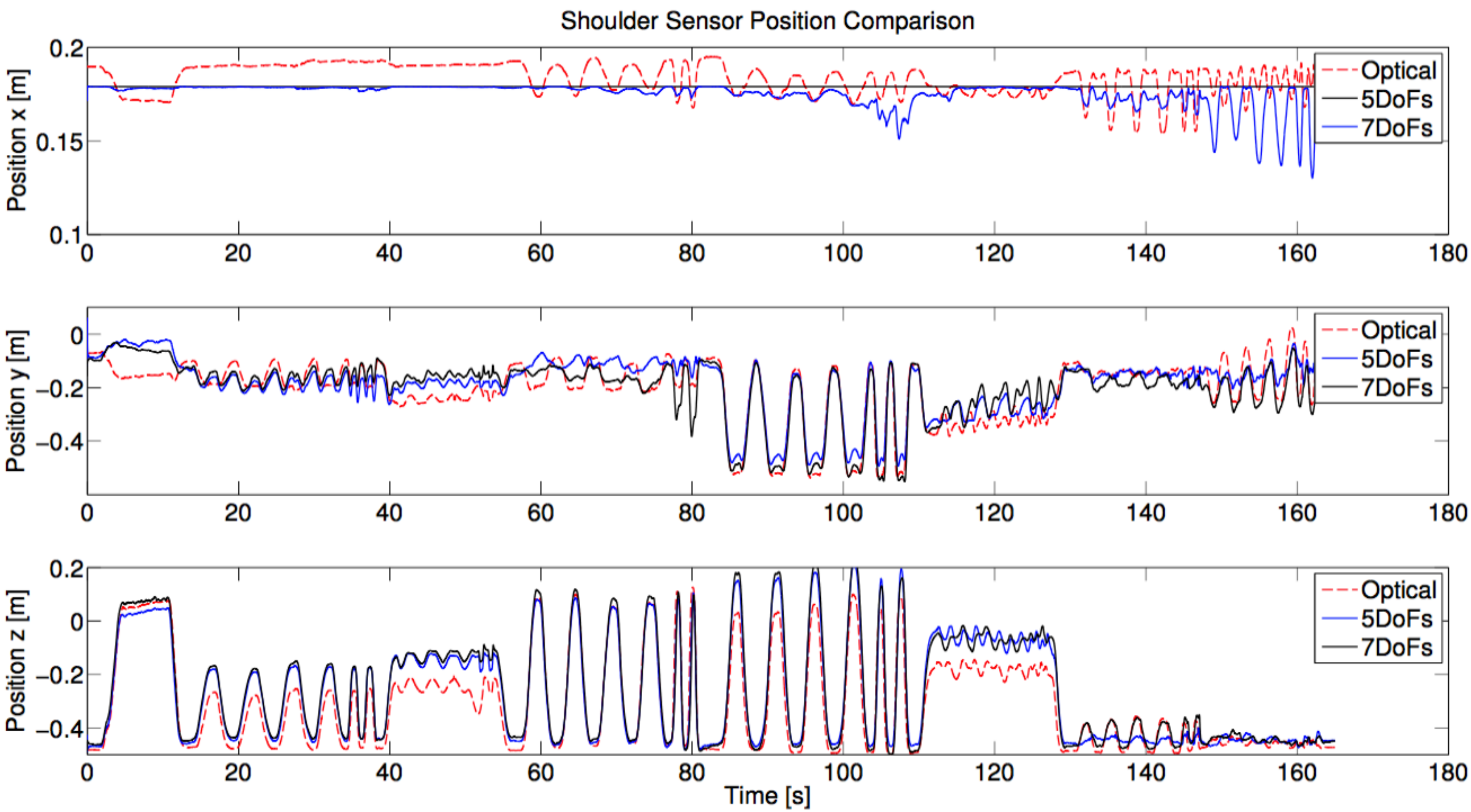

Upperarm Sensor Position Comparison
Position x [m]
0.1
0.2
0.3
0.4
Optical
5DoFs
7DoFs
0
20
40
60
80
100
120
140
160
180
Position y [m]
−0.4
−0.2
0
Optical
5DoFs
7DoFs
0
20
40
60
80
100
120
140
160
180
Position z [m]
−0.2
0
0.2
Optical
5DoFs
7DoFs
0
20
40
60
80
100
120
140
160
180
Time [s]

Position



Forearm Sensor Position Comparison
Position x [m]
Optical
5DoFs
7DoFs
Position y [m]
Optical
5DoFs
7DoFs
Position z [m]
Optical
5DoFs
7DoFs
Time [s]

Position

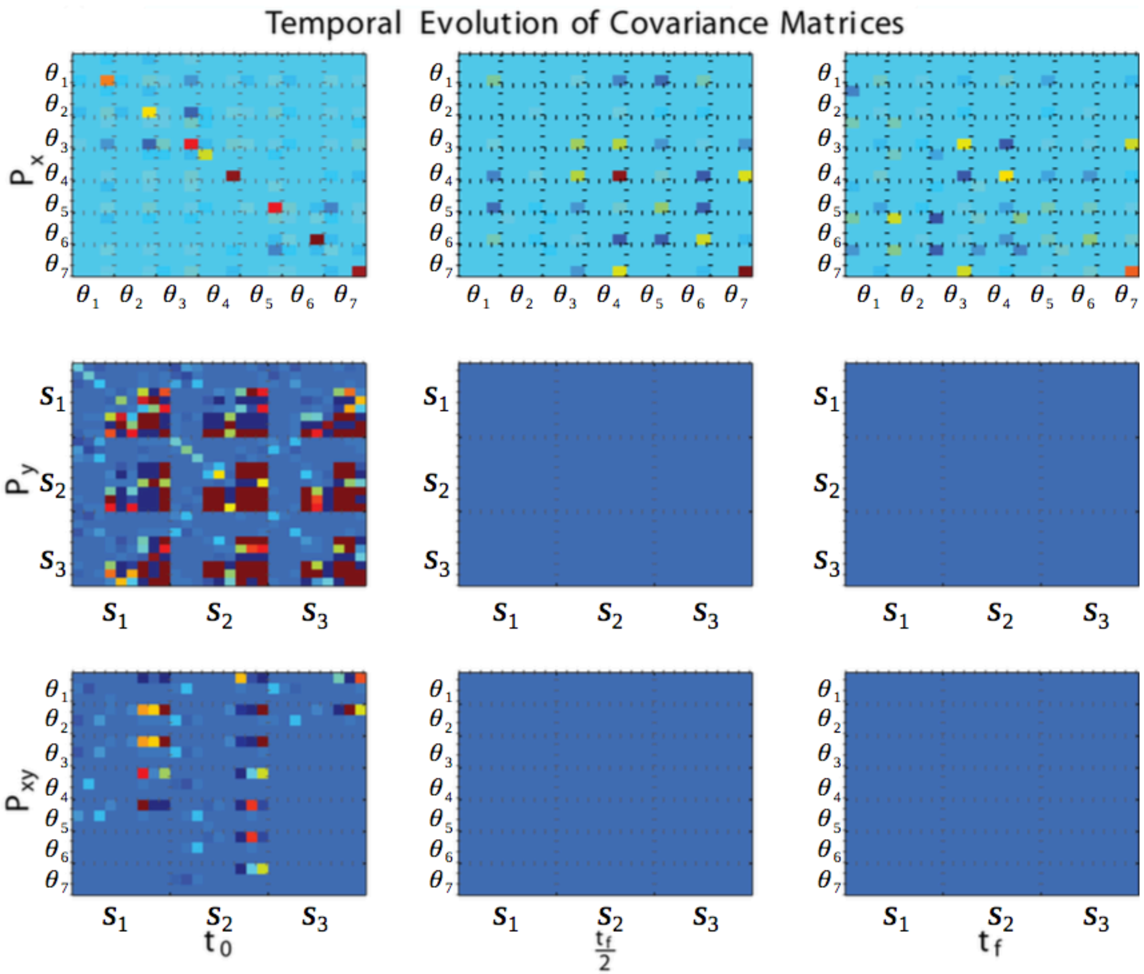

Shoulder Sensor Position Comparison
Position x [m]
0.2
0.15
0.1
Optical
5DoFs
7DoFs
Position y [m]
0
−0.2
−0.4
Position z [m]
0.2
0
−0.2
−0.4
0
20
40
60
80
100
120
140
160
180
Time [s]

Synthetic Results

Variable	$E_{\theta_i,5}$	$E_{\theta_i,7}$	$C_{\theta_i,5}$	$C_{\theta_i,7}$
θ_1	-	6.19	-	0.65
θ_2	-	3.43	-	0.74
θ_3	7.03	8.19	0.95	0.94
θ_4	6.03	10.68	0.87	0.63
θ_5	4.95	8.79	0.99	0.97
θ_6	9.93	5.00	0.98	0.99
θ_7	11.29	9.61	0.85	0.85
Average	7.85	7.41	0.93	0.82

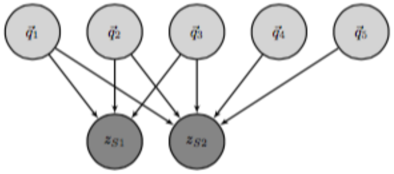
Variable	$E_{P_i,5}$	$E_{P_i,7}$	$C_{P_i,5}$	$C_{P_i,7}$
Shoulder	36.9	34.1	0.97	0.98
IMU arm	76.8	66.5	0.99	0.99
Elbow	70.6	65.5	0.98	0.98
IMU forearm	106.6	103.6	0.98	0.98
Average	72.7	67.4	0.98	0.98

Progress of Correlation



Further Details

- Further extension of the approach brings to the general use of Probabilistic Graphical Models for this task
  - Ruffaldi E., Peppoloni L., Filippeschi A. & Avizzano C.A. (2014). A novel approach to motion tracking with wearable sensors based on Probabilistic Graphical Models. In *Robotics and Automation (ICRA), 2014 IEEE International Conference on* (pp. 1247-1252). . doi:10.1109/ICRA.2014.6907013

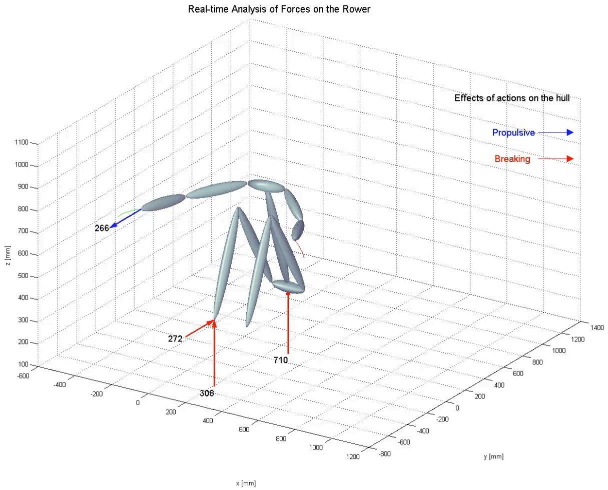


Virtual Sensor Model

- The Bayesian approach allows a general relationship between elements and we can also introduce Virtual Sensors
- Specific case of combining ground sensors with the inertial ones

Virtual Sensor Model

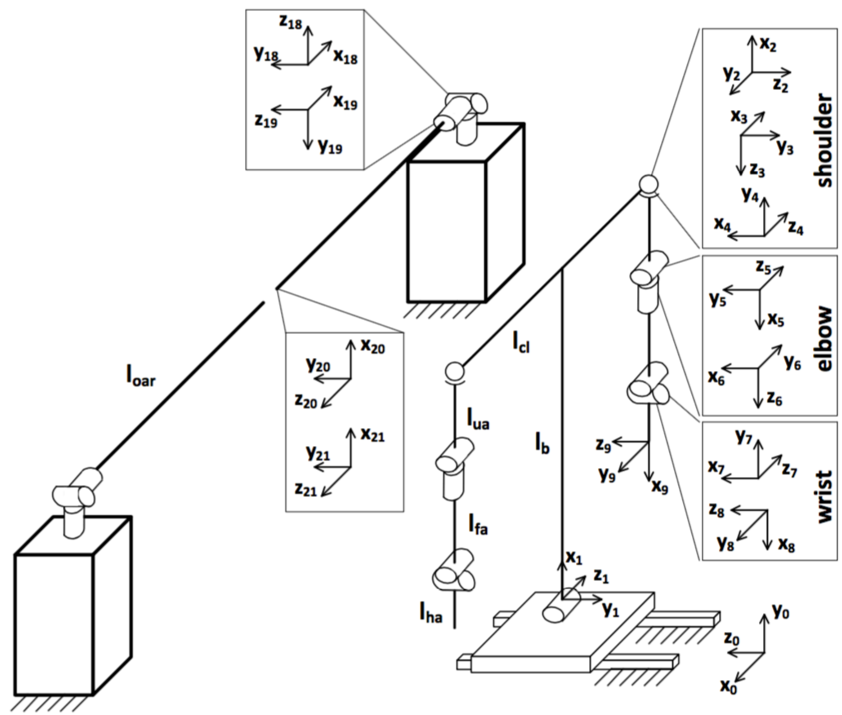
- Objective
  - Provide body tracking based on inertial measures in outdoor environment
  - Taking advantage of existing instrumentation
    - Oar and Seat sensing
  - Sensor fusion between sensing systems



Extraction from Mocap + Force model

Model

- We utilized a 22 DoF model (the 15 DoF for the rower body can be tracked with 5 IMUs instead of 8)
- The closure of the kinematic loop (interfaces between user's hands and oars handles) is enforced through virtual sensors
- The first is an estimate of the position in global coordinates of the attachment point of the hand to the oar, the second is the axis of the oar directed toward the handle



Full D-H Table

Frame	Parent	a	α	d	θ	Joint
1	0	0	$-\pi/2$	q_1	$\pi/2$	Seat (prismatic)
2	1	l_b	$-\pi/2$	l_{cl}^R	q_2	R Back
3	2	0	$\pi/2$	0	$q_3 - \pi/2$	R Shoulder Abduction
4	3	0	$-\pi/2$	0	$q_4 - \pi/2$	R Shoulder Rotation
5	4	l_{ua}^R	0	0	$q_5 - \pi/2$	R Shoulder Flexion
6	5	0	$\pi/2$	0	$\pi/2 + q_6$	R Elbow Flexion
7	6	0	$-\pi/2$	l_{fa}^R	q_7	R Elbow Rotation
8	7	0	$-\pi/2$	0	$q_8 - \pi/2$	R Hand Abduction
9	8	$-l_{ha}^R$	0	0	q_9	R Hand Flexion
10	1	l_b	$\pi/2$	$-l_{cl}^L$	q_2	L Back
11	10	0	$\pi/2$	0	$q_{10} - \pi/2$	L Shoulder Abduction
12	11	0	$-\pi/2$	0	$\pi/2 + q_{11}$	L Shoulder Rotation
13	12	l_{ua}^L	0	0	$q_{12} - \pi/2$	L Shoulder Flexion
14	13	0	$\pi/2$	0	$\pi/2 + q_{13}$	L Elbow Flexion
15	14	0	$-\pi/2$	l_{fa}^L	q_{14}	L Elbow Rotation
16	15	0	$\pi/2$	0	$q_{15} - \pi/2$	L Hand Abduction
17	16	$-l_{ha}^L$	0	0	q_{16}	L Hand Flexion
18	0		see A_{18}^0 in equation 1			R Oar Base
19	18	0	$-\pi/2$	0	q_{18}	R Phi
20	19	0	$\pi/2$	l_{oar}^R	$q_{19} - \pi/2$	R Alpha
21	20	0	0	0	q_{20}	R Rotation
22	0		see A_{22}^0 in equation 1			L Oar Base
23	22	0	$-\pi/2$	0	q_{18}	L Phi
24	23	0	$\pi/2$	l_{oar}^R	$q_{19} - \pi/2$	L Alpha
25	24	0	0	0	q_{20}	L Rotation

Sensor Table

Sensor	Frame	Sensor Type	Name
1	2	Inertial 9D	Back
2	5	Inertial 9D	R Upperarm
3	7	Inertial 9D	R Forearm
4	13	Inertial 9D	L Upperarm
5	15	Inertial 9D	L Forearm
6	1	Position 1D	Seat
7	19	Encoder 1D	R Phi
8	20	Encoder 1D	R Alpha
9	23	Encoder 1D	L Phi
10	24	Encoder 1D	L Alpha

Virtual Sensors

- This is a closed kinematic chain and want to close the hands over the oars
- For implementing this we introduced Virtual Sensors with ZERO observation

$$h_{rp} = r^0_{0,9} - r^0_{0,21} = 0$$

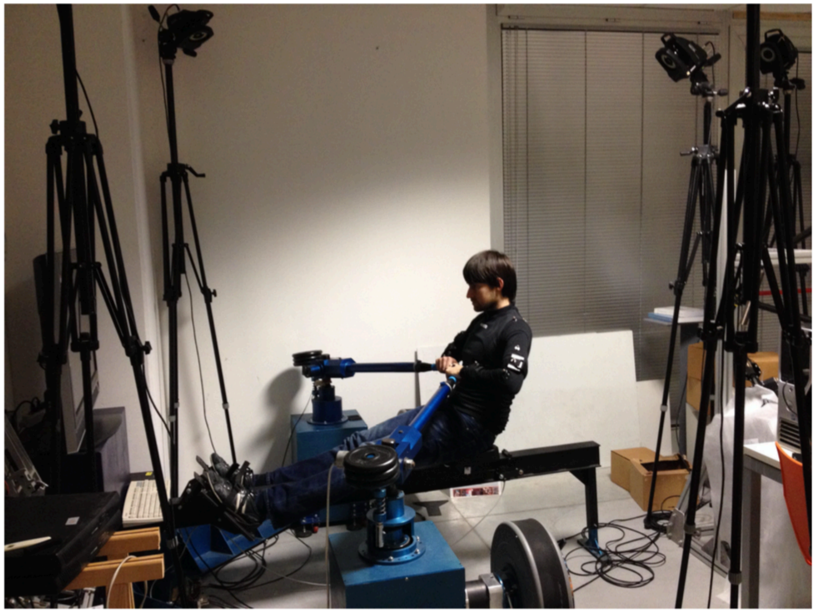
$$h_{rz} = (T_9)_z - (T_{21})_z = 0$$

$$h_{lp} = r^0_{0,17} - r^0_{0,25} = 0$$

$$h_{lz} = (T_{17})_z - (T_{25})_z = 0$$

Validation

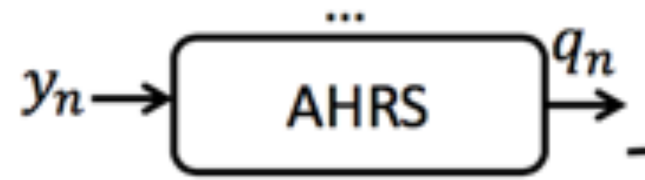
- Kinematic data from an optical mocap session with an expert rower, IMUs measurements generated from the kinematic data plus gaussian noise
- The effects of boat velocity and acceleration was added to the virtual measures
- 5 IMUs, Vicon used as ground truth for body landmarks positions



Result

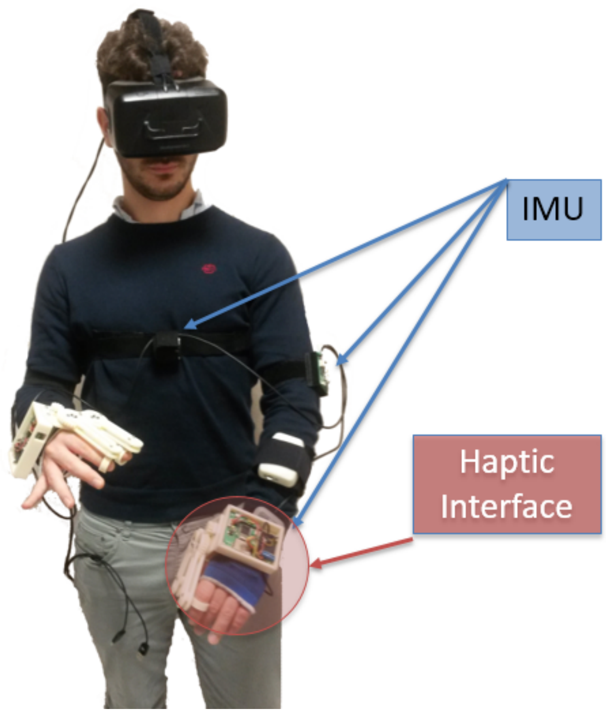
Position	RMSE $[m]$	r
p_{ShR}	0.078	0.3965
p_{ShL}	0.081	0.4814
p_{ElR}	0.158	0.8299
p_{ElL}	0.153	0.9081
p_{WrR}	0.034	0.9913
p_{WrL}	0.054	0.9864

AHR

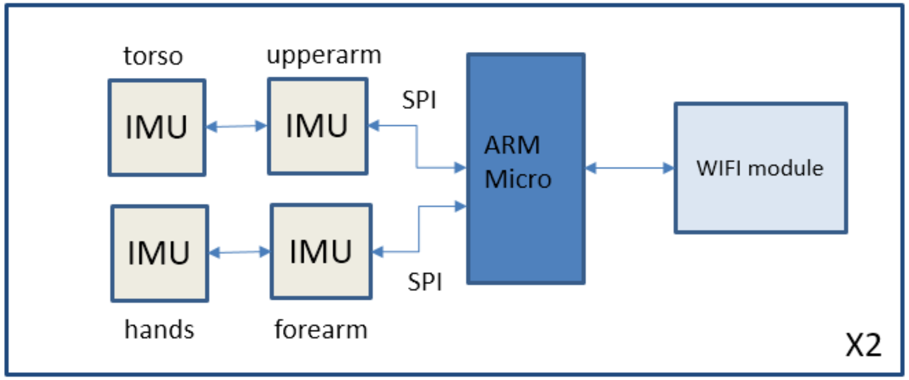


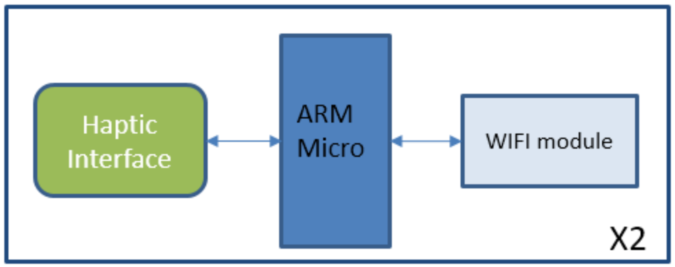
- The AHRS method estimates the quaternion of the IMU given acc/gyro/mag
- Example of usage
  - Graziano A., Tripicchio P., **Ruffaldi E.** & Avizzano C.A. (2016). A wireless haptic data suit for controlling humanoid robots (ISR)

Full Immersive Usage



For each arm:





Graziano A., Tripicchio P., **Ruffaldi E.** & Avizzano C.A. (2016). A wireless haptic data suit for controlling humanoid robots.In *47th International Symposium on Robotics (ISR)* . : VDE Verlag GmbH. isbn:978-380074231-8

IEEE ITALY SECTION
2016 MEDICAL INFORMATICS IS MI SS

INSTITUTE OF COMMUNICATION, INFORMATION AND PERCEPTION TECHNOLOGIES

Scuola Superiore Sant'Anna

PERCRO

A wireless integrated haptic data suit for controlling humanoid robots

A. Graziano, P. Tripicchio,
C.A. Avizzano, E. Ruffaldi

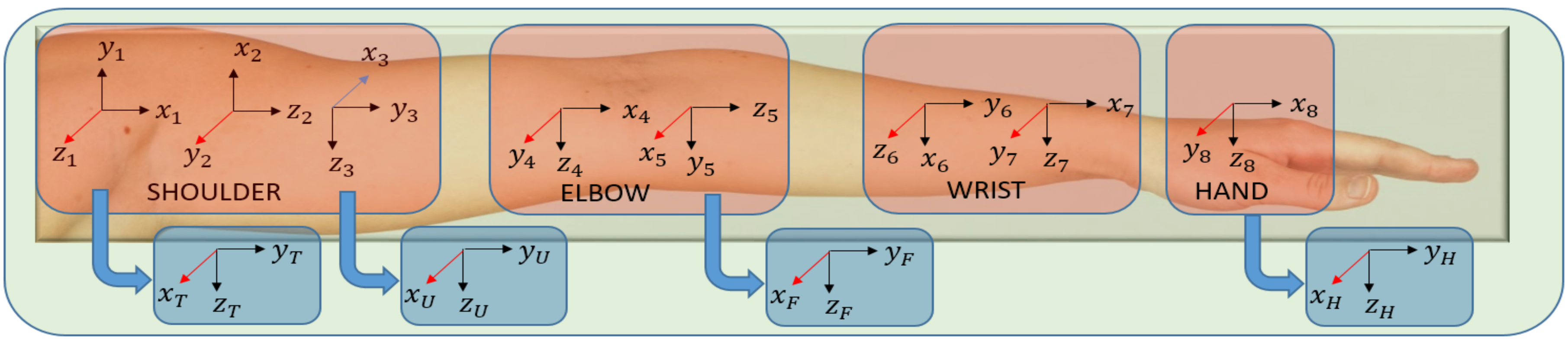
Scuola Superiore Sant'Anna, Pisa, Italy
TeCiP Institute, PERCRO

Pose Estimation

- 7 DoF kinematic chain to model human arm
- Joint angles obtained by estimating relative attitudes of the sensor frames

Frame	a_i	α_i	d_i	θ_i
1	0	$\frac{\pi}{2}$	0	$\theta_1 + \frac{\pi}{2}$
2	0	$\frac{\pi}{2}$	0	$\theta_2 - \frac{\pi}{2}$
3	l_{ua}	0	0	$\theta_3 + \frac{\pi}{2}$
4	0	$\frac{\pi}{2}$	0	$\theta_4 + \frac{\pi}{2}$
5	0	$\frac{\pi}{2}$	l_{fa}	$\theta_5 + \frac{\pi}{2}$
6	0	$\frac{\pi}{2}$	0	$\theta_6 + \frac{\pi}{2}$
7	0	0	0	θ_7

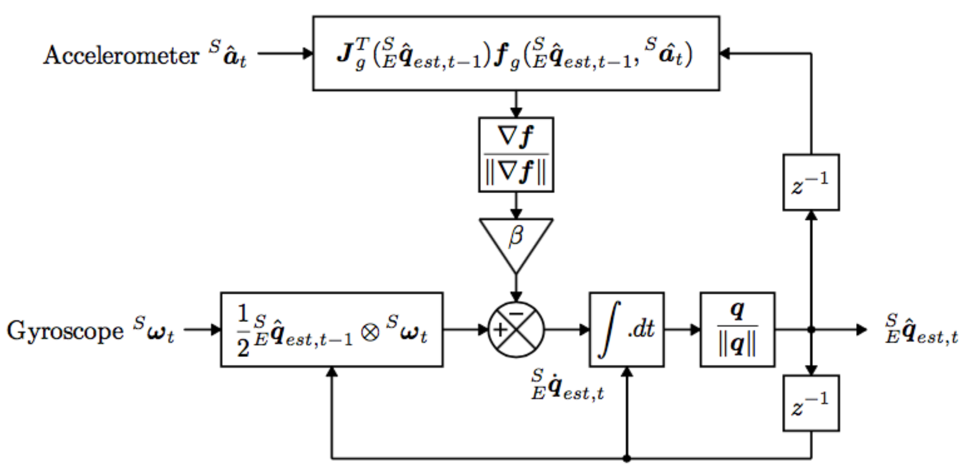
D-H



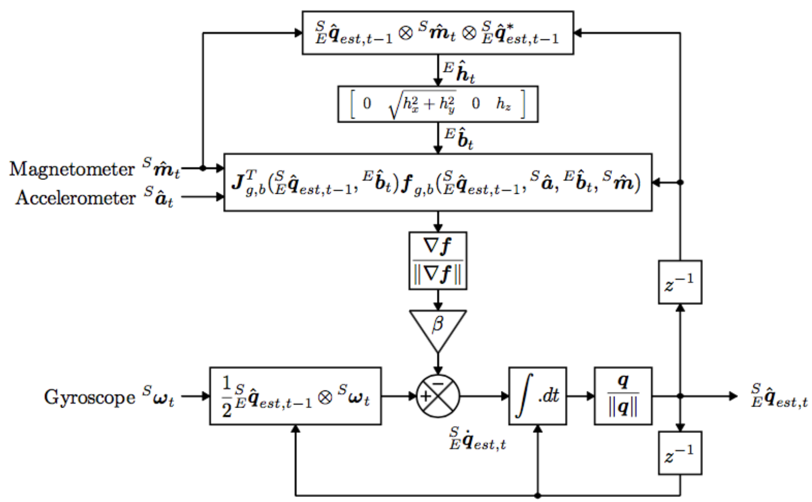
AHRS Madgwick

- Attitude and heading reference system is based on the fusion of the sensors (locally) compensating the drift in the dynamic data (acceleration and angular velocity) by using reference directions (gravity and magnetic north)
- Madgwick, Sebastian OH, Andrew JL Harrison, and Ravi Vaidyanathan. "Estimation of IMU and MARG orientation using a gradient descent algorithm." *2011 IEEE International Conference on Rehabilitation Robotics*. IEEE, 2011.
- Based on Quaternion Mathematics

Without MAG



With MAG



AHRS Madgwick

Forward Part

$$^{S}\boldsymbol{\omega} = \begin{bmatrix} 0 & \omega_x & \omega_y & \omega_z \end{bmatrix}$$

$$^{S}_{E}\dot{\boldsymbol{q}} = \frac{1}{2}\,^{S}_{E}\hat{\boldsymbol{q}} \otimes {}^{S}\boldsymbol{\omega}$$

→

$$^{S}_{E}\dot{\boldsymbol{q}}_{\omega,t} = \frac{1}{2}\,^{S}_{E}\hat{\boldsymbol{q}}_{est,t-1} \otimes {}^{S}\boldsymbol{\omega}_t$$

$$^{S}_{E}\boldsymbol{q}_{\omega,t} = {}^{S}_{E}\hat{\boldsymbol{q}}_{est,t-1} + {}^{S}_{E}\dot{\boldsymbol{q}}_{\omega,t}\Delta t$$

AHRS Madgwick

Forward Part

$$^{S}\boldsymbol{\omega} = \begin{bmatrix} 0 & \omega_x & \omega_y & \omega_z \end{bmatrix}$$

$$^{S}_{E}\dot{\boldsymbol{q}} = \frac{1}{2}\,^{S}_{E}\hat{\boldsymbol{q}} \otimes {}^{S}\boldsymbol{\omega}$$

$$^{S}_{E}\dot{\boldsymbol{q}}_{\omega,t} = \frac{1}{2}\,^{S}_{E}\hat{\boldsymbol{q}}_{est,t-1} \otimes {}^{S}\boldsymbol{\omega}_t$$

$$^{S}_{E}\boldsymbol{q}_{\omega,t} = {}^{S}_{E}\hat{\boldsymbol{q}}_{est,t-1} + {}^{S}_{E}\dot{\boldsymbol{q}}_{\omega,t}\Delta t$$

Alignment of orientation with the gravity
(minimization)

$$^{S}_{E}\boldsymbol{q}_{k+1} = {}^{S}_{E}\hat{\boldsymbol{q}}_k - \mu \frac{\nabla \boldsymbol{f}({}^{S}_{E}\hat{\boldsymbol{q}}_k, {}^{E}\hat{\boldsymbol{d}}, {}^{S}\hat{\boldsymbol{s}})}{\left\| \nabla \boldsymbol{f}({}^{S}_{E}\hat{\boldsymbol{q}}_k, {}^{E}\hat{\boldsymbol{d}}, {}^{S}\hat{\boldsymbol{s}}) \right\|},\ k = 0, 1, 2 \dots n \quad (7)$$

$$\nabla \boldsymbol{f}({}^{S}_{E}\hat{\boldsymbol{q}}_k, {}^{E}\hat{\boldsymbol{d}}, {}^{S}\hat{\boldsymbol{s}}) = \boldsymbol{J}^T({}^{S}_{E}\hat{\boldsymbol{q}}_k, {}^{E}\hat{\boldsymbol{d}})\boldsymbol{f}({}^{S}_{E}\hat{\boldsymbol{q}}_k, {}^{E}\hat{\boldsymbol{d}}, {}^{S}\hat{\boldsymbol{s}}) \quad (8)$$

Madgwick

$$^S_E\hat{\boldsymbol{q}} = \begin{bmatrix} q_1 & q_2 & q_3 & q_4 \end{bmatrix}$$

$$^E\hat{\boldsymbol{g}} = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^S\hat{\boldsymbol{a}} = \begin{bmatrix} 0 & a_x & a_y & a_z \end{bmatrix}$$

$$\boldsymbol{f}_g({}^S_E\hat{\boldsymbol{q}}, {}^S\hat{\boldsymbol{a}}) = \begin{bmatrix} 2(q_2q_4 - q_1q_3) - a_x \\ 2(q_1q_2 + q_3q_4) - a_y \\ 2(\frac{1}{2} - q_2^2 - q_3^2) - a_z \end{bmatrix}$$

$$\boldsymbol{J}_g({}^S_E\hat{\boldsymbol{q}}) = \begin{bmatrix} -2q_3 & 2q_4 & -2q_1 & 2q_2 \\ 2q_2 & 2q_1 & 2q_4 & 2q_3 \\ 0 & -4q_2 & -4q_3 & 0 \end{bmatrix}$$

$$^E\hat{\boldsymbol{b}} = \begin{bmatrix} 0 & b_x & 0 & b_z \end{bmatrix}$$

$$^S\hat{\boldsymbol{m}} = \begin{bmatrix} 0 & m_x & m_y & m_z \end{bmatrix}$$

$$\boldsymbol{f}_b({}^S_E\hat{\boldsymbol{q}}, {}^E\hat{\boldsymbol{b}}, {}^S\hat{\boldsymbol{m}}) = \begin{bmatrix} 2b_x(0.5 - q_3^2 - q_4^2) + 2b_z(q_2q_4 - q_1q_3) - m_x \\ 2b_x(q_2q_3 - q_1q_4) + 2b_z(q_1q_2 + q_3q_4) - m_y \\ 2b_x(q_1q_3 + q_2q_4) + 2b_z(0.5 - q_2^2 - q_3^2) - m_z \end{bmatrix}$$

$$\boldsymbol{J}_b({}^S_E\hat{\boldsymbol{q}}, {}^E\hat{\boldsymbol{b}}) = \begin{bmatrix} -2b_zq_3 & 2b_zq_4 & -4b_xq_3 - 2b_zq_1 & -4b_xq_4 + 2b_zq_2 \\ -2b_xq_4 + 2b_zq_2 & 2b_xq_3 + 2b_zq_1 & 2b_xq_2 + 2b_zq_4 & -2b_xq_1 + 2b_zq_3 \\ 2b_xq_3 & 2b_xq_4 - 4b_zq_2 & 2b_xq_1 - 4b_zq_3 & 2b_xq_2 \end{bmatrix}$$

Madgwick

- Convergence Rate

$$\mu_t = \alpha \left\| {}^S_E\dot{\boldsymbol{q}}_{\omega,t} \right\| \Delta t,\ \ \alpha > 1$$

- Fusion of inertial and fixed

$${}^S_E\boldsymbol{q}_{est,t} = \gamma_t {}^S_E\boldsymbol{q}_{\nabla,t} + (1-\gamma_t) {}^S_E\boldsymbol{q}_{\omega,t},\ \ 0 \leq \gamma_t \leq 1$$

Communication Issues

- In two iterations of the technology we explored two communication means
  - Bluetooth 2.0 – good bandwidth
    - Limited to 8 devices
    - One-to-one connection to computer
    - Protocol issues
    - Typically only serial emulation (guaranteed)
  - WiFi – high bandwidth more robust
    - Larger distance
    - Number of devices is limited by access point

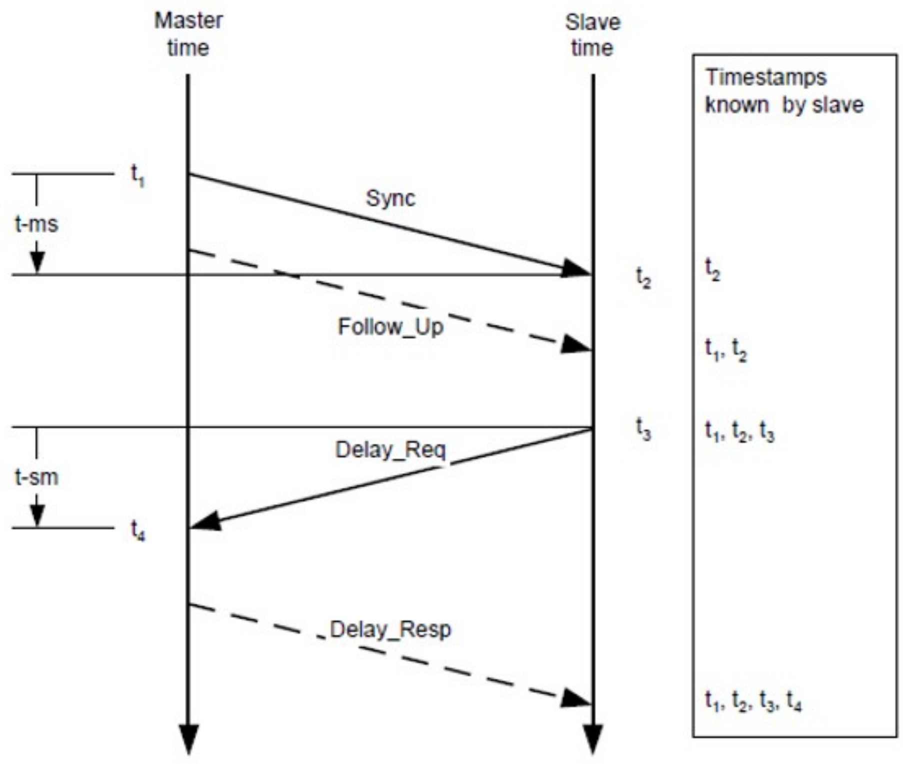
- Synchronization: PTP - Precision Timing Protocol

Precision Timing Protocol

- Relatively simple protocol that allows to synchronized the timing between two machines
  - Daemons for Linux/OSX do exist
  - Embeddable implementation https://github.com/eruffaldi/tinyptp
- References
  - Cho, Hyuntae, et al. "Precision time synchronization using IEEE 1588 for wireless sensor networks." *Computational Science and Engineering, 2009. CSE'09. International Conference on*. Vol. 2. IEEE, 2009.

Precision Time Protocol

- Objective: measure delay between two clocks independently of the network delay



BIOMECHANICAL ASSESSMENT

Traditional Assessment

- How to take into account several factors interacting at the same time?
- In general it has been shown that methods assessing different factors lead to different risk evaluations.
- How to keep up with the cost increase (money and time) due to the use of more than one method?

Ergonomic assessment

- Several methods for ergonomic assessment cited by ISO 11228 and UNI-EN 1005 regulations

Method	Description	Output
RULA	Analysis of postures of different body segments; it also considers their frequency during a work shift	Quantitative
OCRA ckl	Semi-detailed method that considers, in a simplified way, the same risk factors as the OCRA index. Exposure level is classified in the three-zone system. Applicable also to multitask repetitive jobs.	Quantitative
HAL	Detailed method (for monotask handwork lasting almost 4 h per shift) mainly based on the analysis of frequency of actions (in relation to duty cycle) and of peak force; other main factors are generically considered.	Quantitative
NIOSH Lifting Index	Evaluation of the risks related to manual handling of load during lifting tasks	Quantitative
OWAS	Analysis of postures of different body segments; it also considers their frequency during a work shift	Quantitative

Rapid Upper Limb Assessment

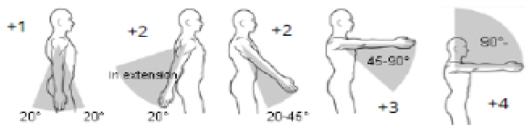
http://ergo-plus.com/wp-content/uploads/RULA.pdf

- Synthetic Index of Risk

Score	Level of MSD Risk
1-2	negligible risk, no action required
3-4	low risk, change may be needed
5-6	medium risk, further investigation, change soon
6+	very high risk, implement change now

A. Arm and Wrist Analysis

Step 1: Locate Upper Arm Position:



Step 1a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score

Step 2: Locate Lower Arm Position:

Lower Arm Score

Step 2a: Adjust...
If either arm is working across midline or out to side of body: Add +1

Step 3: Locate Wrist Position:

Step 3a: Adjust...
If wrist is bent from midline: Add +1

Step 4: Wrist Twist:
If wrist is twisted in mid-range: +1
If wrist is at or near end of range: +2

Wrist Twist Score — Wrist Score

Step 5: Look-up Posture Score in Table A:
Using values from steps 1-4 above, locate score in Table A

Posture Score A
+

Step 6: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

Muscle Use Score
+

Step 7: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

Force / Load Score
=

Step 8: Find Row in Table C
Add values from steps 5-7 to obtain Wrist and Arm Score. Find row in **Table C.**

Wrist & Arm Score

Scores

Table A		Wrist Score 1		Wrist Score 2		Wrist Score 3		Wrist Score 4	
Upper Arm	Lower Arm	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Table C	Neck, Trunk, Leg Score 1	2	3	4	5	6	7+
Wrist / Arm Score 1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

Scoring: (final score from Table C)
1-2 = acceptable posture
3-4 = further investigation, change may be needed
5-6 = further investigation, change soon
7 = investigate and implement change

RULA Score

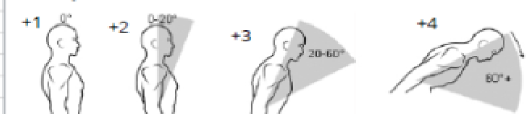
B. Neck, Trunk and Leg Analysis

Step 9: Locate Neck Position:

Neck Score

Step 9a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 10: Locate Trunk Position:



Step 10a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Trunk Score

Step 11: Legs:
If legs and feet are supported: +1
If not: +2

Leg Score

Neck Posture Score	Table B: Trunk Posture Score 1		2		3		4		5		6	
	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Step 12: Look-up Posture Score in Table B:
Using values from steps 9-11 above, locate score in Table B

Posture B Score
+

Step 13: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

Muscle Use Score
+

Step 14: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

Force / Load Score
=

Step 15: Find Column in Table C
Add values from steps 12-14 to obtain Neck, Trunk and Leg Score. Find Column in **Table C.**

Neck, Trunk, Leg Score

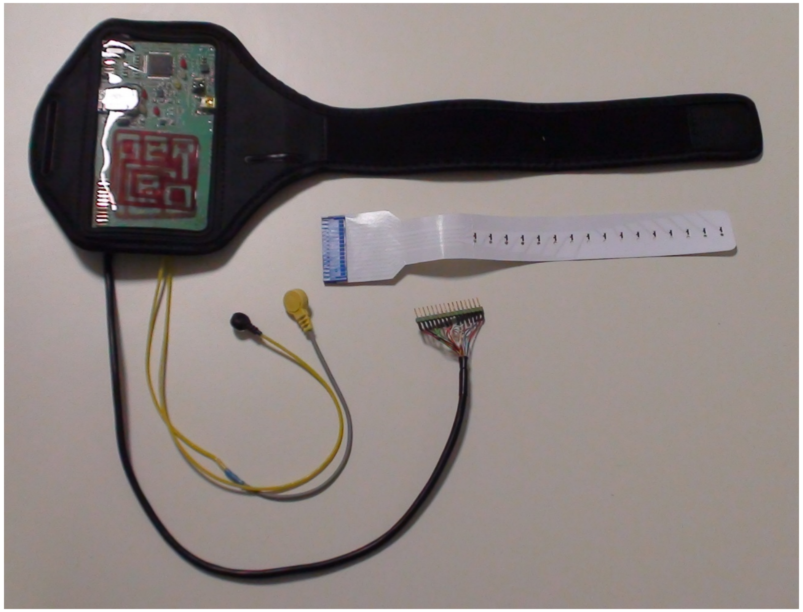
Original Worksheet Developed by Dr. Alan Hedge. Based on RULA: a survey method for the investigation of work-related upper limb disorders, McAtamney & Corlett, Applied Ergonomics 1993, 24(2), 91-99

Proposed System

- A novel wearable wireless system capable of assessing the muscular efforts and postures of the human upper limb for WMSDs diagnosis.
- The system can be used to monitor workers in ecologic environment while they are carrying on their everyday tasks.
- The system provides a real-time assessment obtained according to two standard indexes for the analysis of risk factors on workplaces: the Rapid Upper Limb Assessment (RULA) and the Strain Index (SI).

Setup

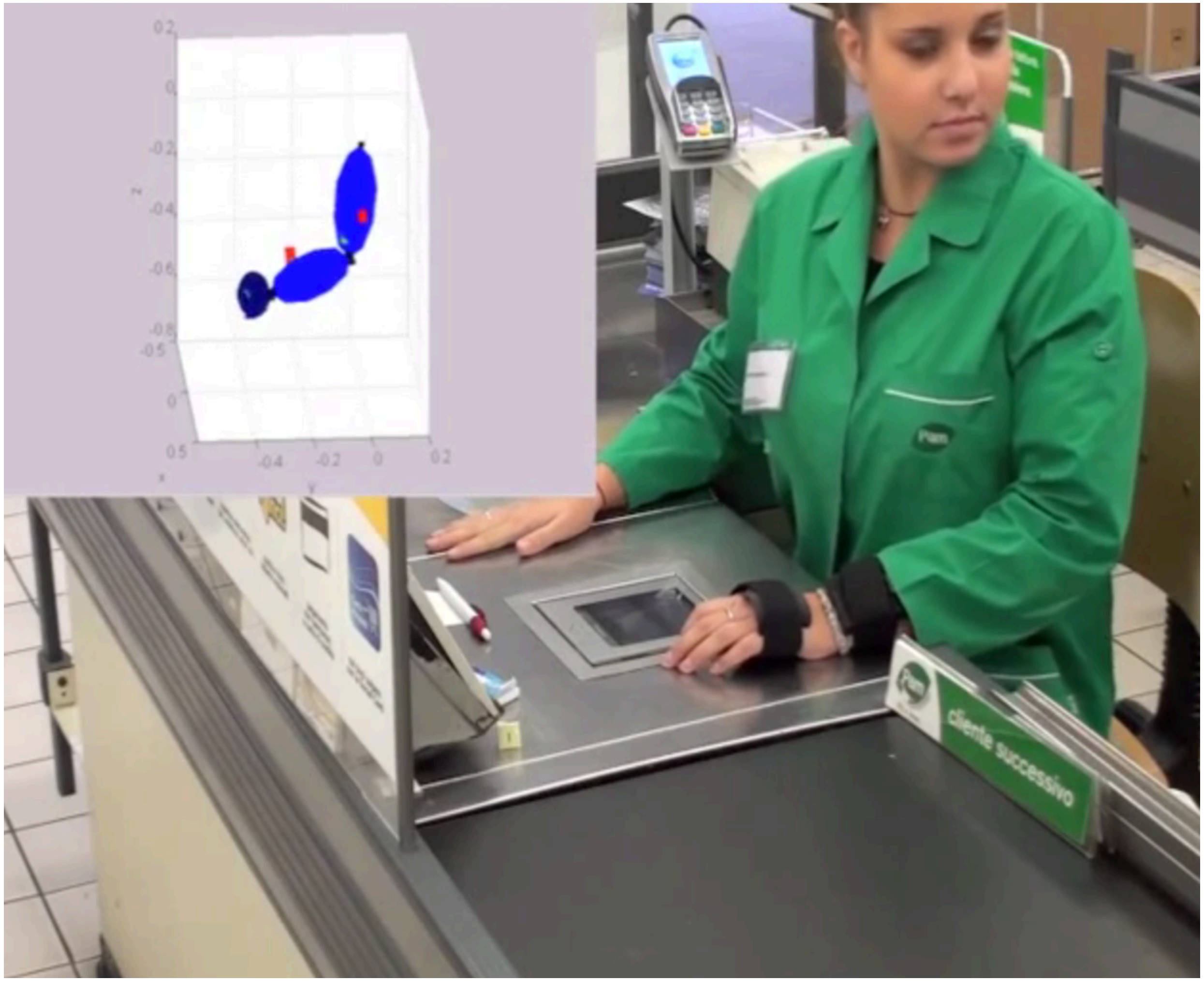
- Fully werable board supporting:
- STM32F micro
- 4 Invensense 9150 IMUs:
  - 3 axes accelerometer
  - 3 axes gyroscope
  - 3 axes magnetometer
- 32 EMG channels
- Maximum sampling frequencies
  - IMUs @ 100 Hz
  - EMG @ 500 Hz
- On-board EMG filtering and feature calculation



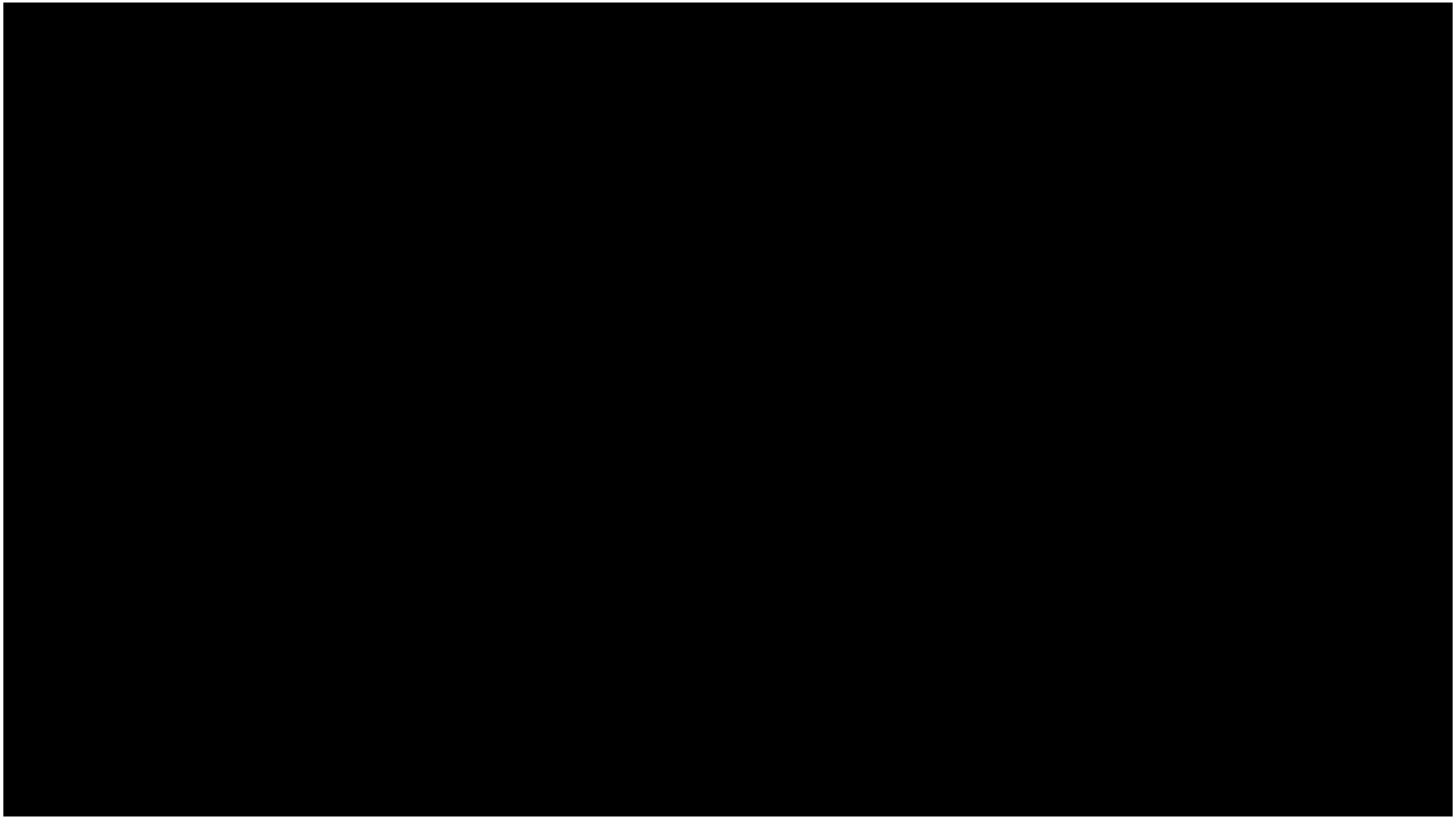
Calibration

IEEE ITALY SECTION 2016 MEDICAL INFORMATICS MISS

Real Case Study



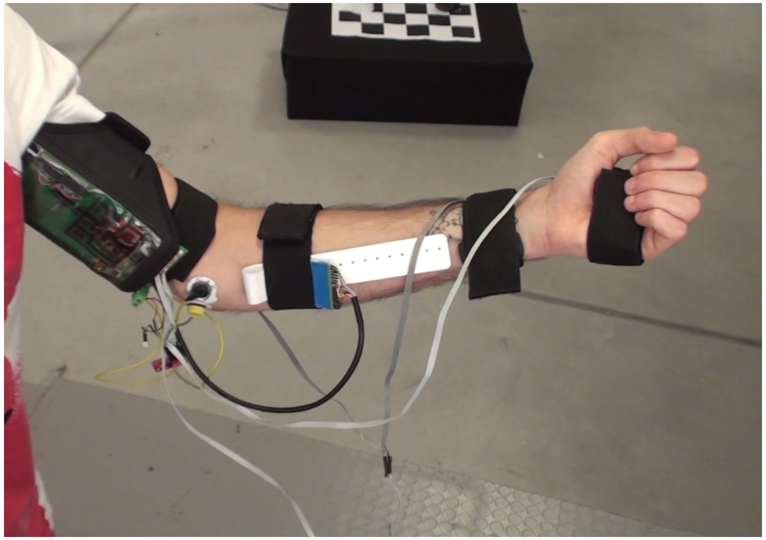
https://www.youtube.com/watch?v=Q5elPTjezVc



IEEE ITALY SECTION 2016 MEDICAL INFORMATICS ISMISS

The System Hardware

- CPU: STM32F4
- EMG: 8 channels (up to 32)
- IMUs: 9-axis MPU9150
- Bluetooth 2.0
- Webserver on host PC

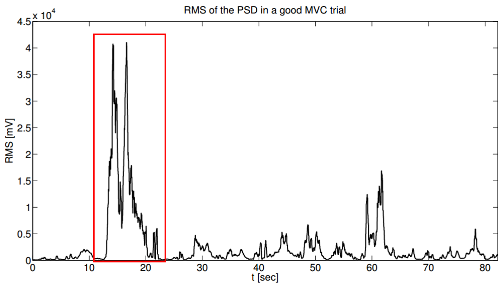


Experimental Setup

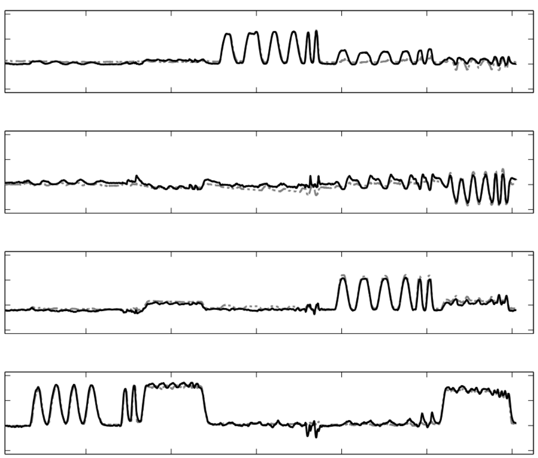
- Task: market cashier check-out operations.
- Ten healthy subjects monitored for two check-out operations each.
- Subjects operated in a station ergonomically identical to the real check-out position.
- Every trial was evaluated by two human evaluators to be used as a ground-truth.
- The system practicability was assessed with questionnaires.

Item	Weight [Kg]
Coke cans pack	2.160
Bisquits pack (small)	0.270
Tuna cans pack	0.440
Cornflakes pack	0.365
Tea bottle	1.620
Potato bag	4.020
Bisquits pack (big)	0.510

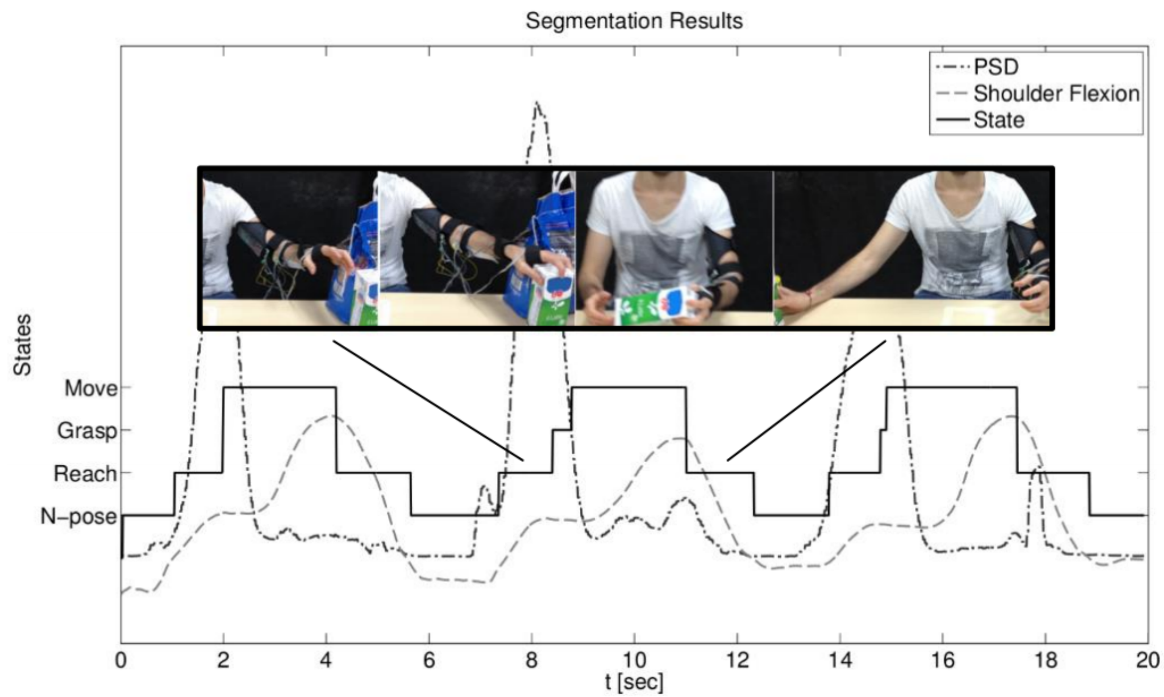
Task Segmentation



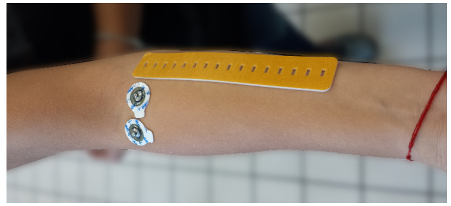
EMG Features



$$q/\dot{q}$$



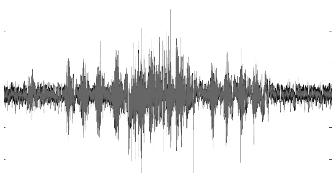
Muscular activation

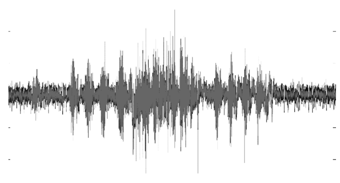


8 Channels

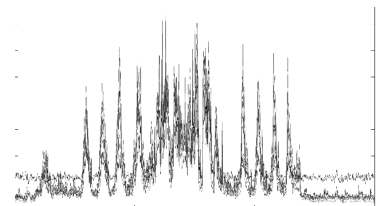
EMG

Raw Signals → Bandpass Filter [20 - 200] Hz → RMS → Windows 128ms





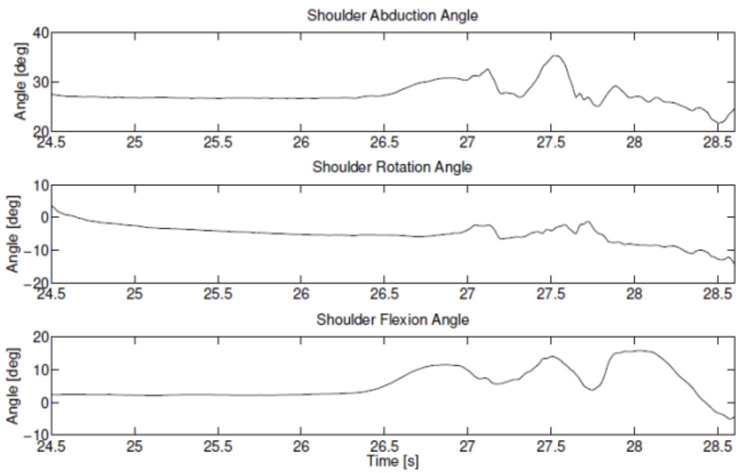
MVC

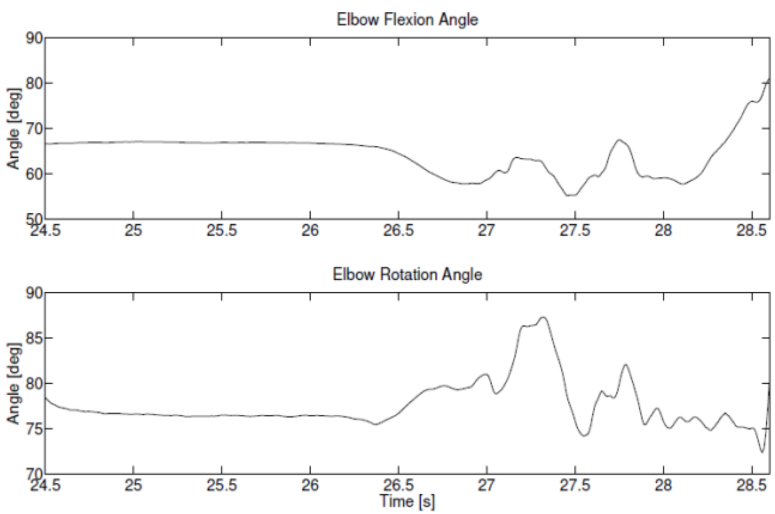


Muscular activation triggers

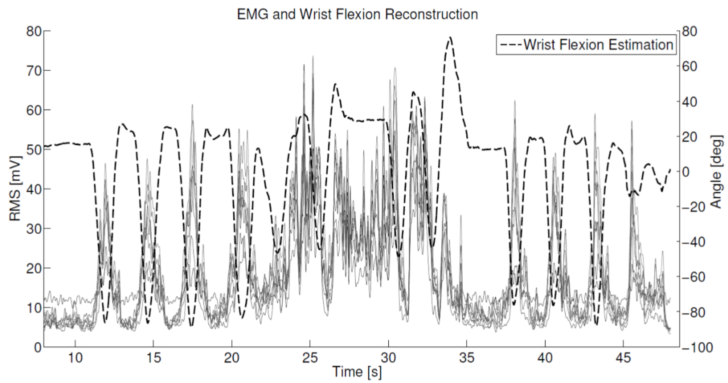
Muscular activity intensity measurement

Results

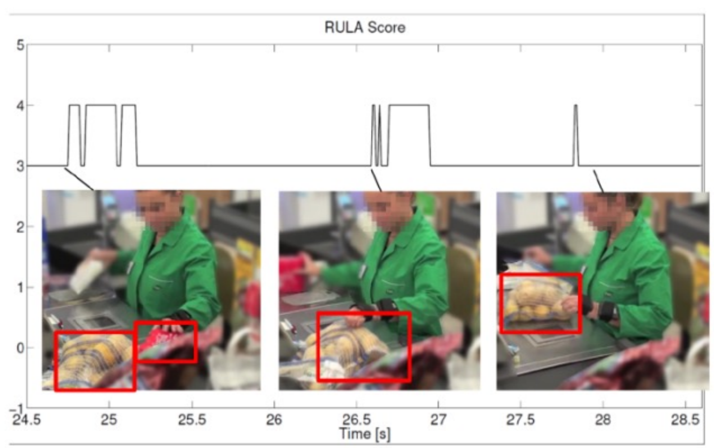




Muscular Activity

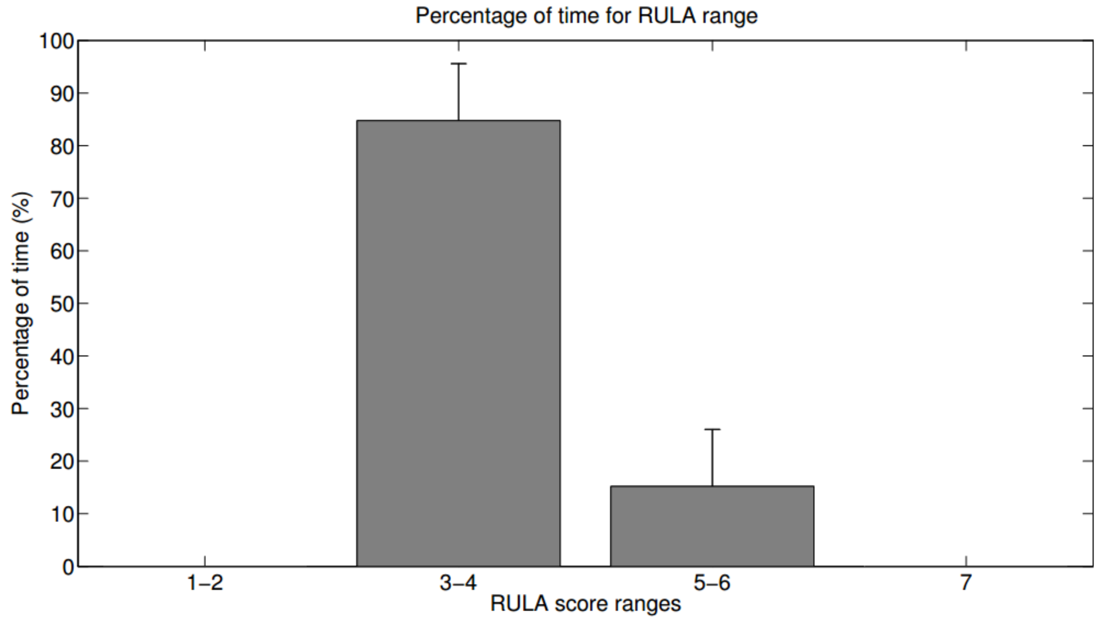


RULA Scores



Results

- Percentage of time spent in every RULA score range by every subject

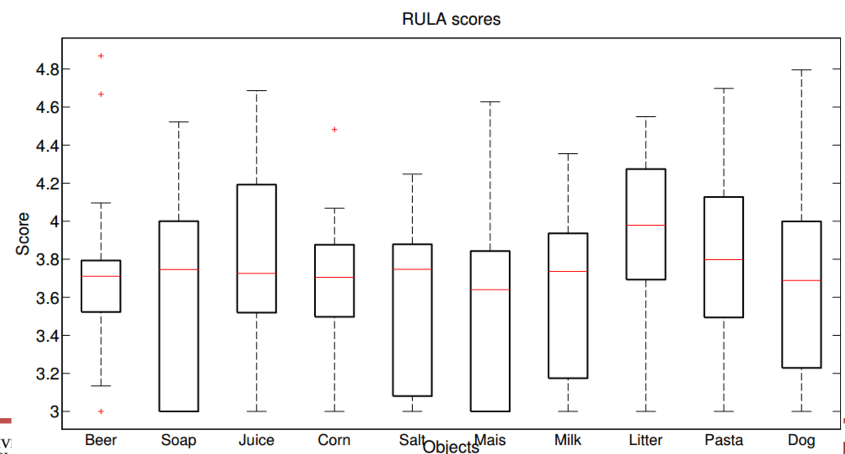


Results

- Comparisons with the human evaluators

Measure	Accuracy %
RULA Action Level	94.79%
SI	44.79%

- System repeatability



Results

- Data were tested for homogeneity with Levene's test.
- A two-way ANOVA was performed on the RULA action level with factors being objects and evaluator type.
- The factor object was found to affect the RULA action level . $(p < 10^4)$
- The factor evaluator type was not significant
- The interaction effect is negligible.

Results

- Wearability assessment of the system, according to questionnaires given to all the subjects. The mean values are shown on according on a Likert scale from 1 to 7.

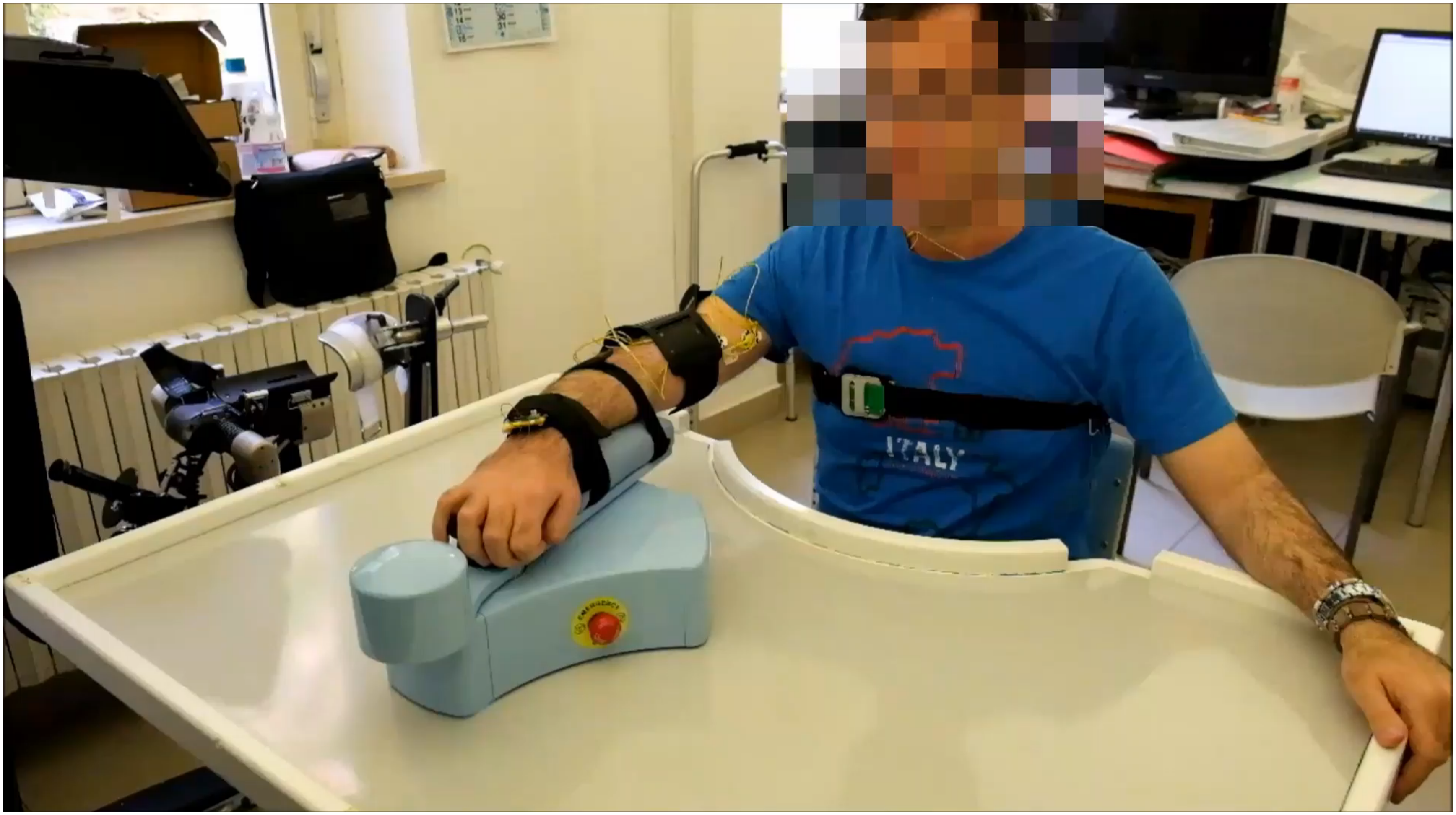
Parameter	Score %
Comfort	5.2
Encumbrance	2
Usability for a complete work turn	5.3

Peppoloni L., Filippeschi A., **Ruffaldi E.** & Avizzano C.A. (2015). A novel wearable system for the online assessment of risk for biomechanical load in repetitive efforts. *International Journal of Industrial Ergonomics*, (in press), . doi:10.1016/j.ergon.2015.07.002

Applications to Tele-Medicine

- Remote control of a Robot for Diagnosis (e.g. FP7 REMEDI, next talk of Avizzano)
- Remote control of a Service Robot for Impaired patients (e.g. H2020 RAMCIP)
- Tele-monitoring (e.g. MOTORE Device, next)

Applications to Tele-Medicine



System Output

Current Action related information

Current Cycle related information

Discussions

- The system is able to give a RULA score estimation congruent to the human evaluators.
- The score associated to every object is repeatable, despite the high variability among subjects (grasp types,…)
- The Cat litter item (heaviest and less comfortable to grasp) has the highest RULA score.
- The lowest score is associated to the Sweet corn can item, that is the lightest and the most easily graspable.

Discussions

- The system gives a SI score congruent to the evaluators in almost the 50% of the cases.
- SI score depends on the intensity of exertion requiring a MVC test.
- As pointed out in [8]:
  - The goodness of the test varies significantly according to the trigger threshold for the intensity of exertion.
  - High-frequency acyclic movements produce artifacts in the EMG signals, that may affect the SI score.

Conclusions

- This work presents a wireless wearable system for online assessment of WMSDs risks for the upper limb.
- The system performs an online score computation according the RULA and SI scoring methods.
- The scores estimated with the proposed approach proved to be congruent with the analysts' scores.
- The users rated the system to be usable for a whole average working turn, being not obstructive or painful during the movements.

Future Directions

- Reduce the dependency on Magnetometer (improvides the applicability)
- Use of Machine-Learning for automatic segmenting the motion phases
  - Finer analysis of complex actions

Related Works

- **Ruffaldi E.**, Peppoloni L. & Filippeschi A. (2015). Sensor fusion for complex articulated body tracking applied in rowing. *Journal of Sport Engineering and Technology*, 229(2), (pp. 92-102). doi:10.1177/1754337115583199
- Peppoloni L., Filippeschi A., **Ruffaldi E.** & Avizzano C.A. (2015). A novel wearable system for the online assessment of risk for biomechanical load in repetitive efforts. *International Journal of Industrial Ergonomics*, (in press), . doi:10.1016/j.ergon.2015.07.002
- Peppoloni L., Filippeschi A., **Ruffaldi E.** & Avizzano C.A. (2013). A novel 7 degrees of freedom model for upper limb kinematic reconstruction based on wearable sensors. In*Intelligent Systems and Informatics (SISY), 2013 IEEE 11th International Symposium on* (pp. 105-110). . doi:10.1109/SISY.2013.6662551

Thanks!

Bibliography

[1] Italian Government Agency for Injured Workers (AMNIL), I disturbi muscolo-scheletrici e da sovraccarico biomeccanico dei lavoratori nel settore 395 del commercio: un quadro comparato, http://www.anmil.it/Portals/0/campagne/patologie_muscolo-scheletriche/Il%20rapporto.pdf (2013).

[2] N. Vignais, M. Miezal, G. Bleser, K. Mura, D. Gorecky, F. Marin, Innovative system for real-time ergonomic feedback in industrial manufacturing, Applied ergonomics 44 (4) (2013).

[3] R. G. Radwin, Automated video exposure assessment of repetitive motion, in: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Vol. 55, SAGE Publications, 2011.

[4] J. P. Mogk, P. J. Keir, Prediction of forearm muscle activity during gripping, Ergonomics 49 (11) (2006) 1121.

[5] A. Franzblau, T. J. Armstrong, R. A. Werner, S. S. Ulin, A cross-sectional assessment of the acgih tlv for hand activity level, Journal of occupational rehabilitation 15 (1) (2005).

[6] A. Freivalds, Y. Kong, H. You, S. Park, A comprehensive risk assessment model for work-related musculoskeletal disorders of the upper extremities, 440 in: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Vol. 44, SAGE Publications, 2000.

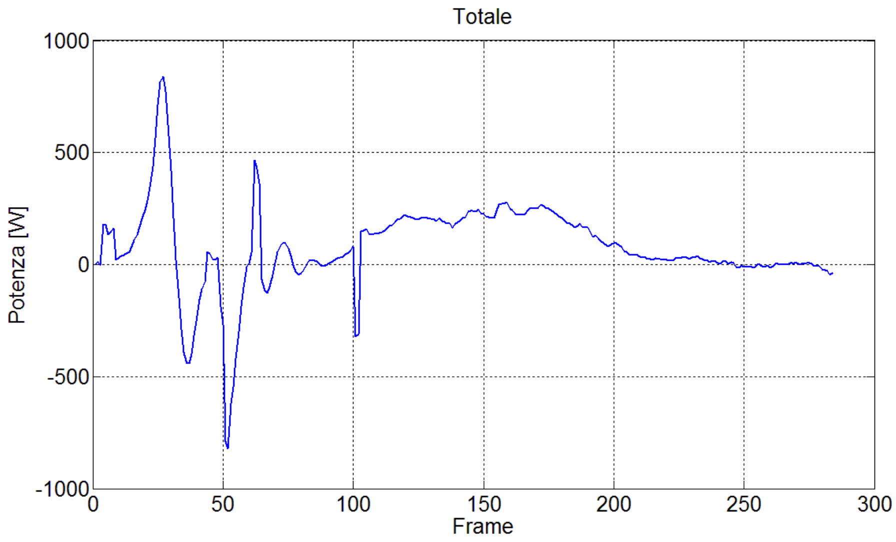
[7] M. E. Chiasson, D. Imbeau, K. Aubry, A. Delisle, Comparing the results of eight methods used to evaluate risk factors associated with musculoskeletal disorders, International Journal of Industrial Ergonomics 42 (5) (2012).

[8] J. M. Cabecas, The risk of distal upper limb disorder in cleaners: A modified application of the strain index method, International journal of industrial ergonomics 37 (6) (2007)

MORE ON VANTS

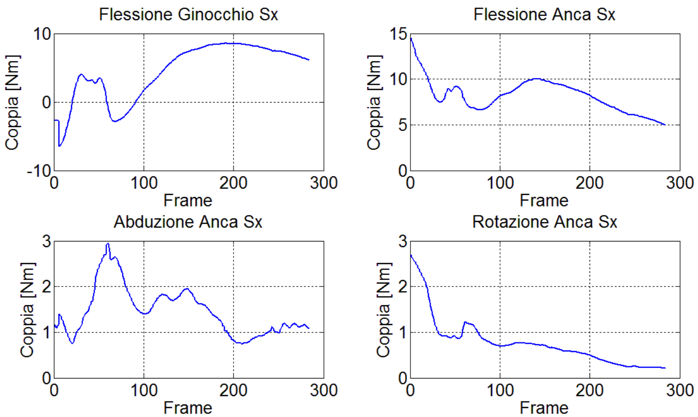
Biomechanical Analysis of the Task

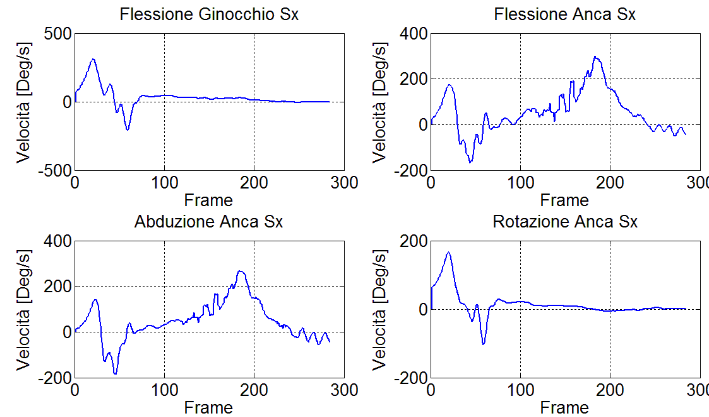
- Results
- Total Task Energy 495 J
- Average power 209 W
- Peak power 838 W
- Total power profile

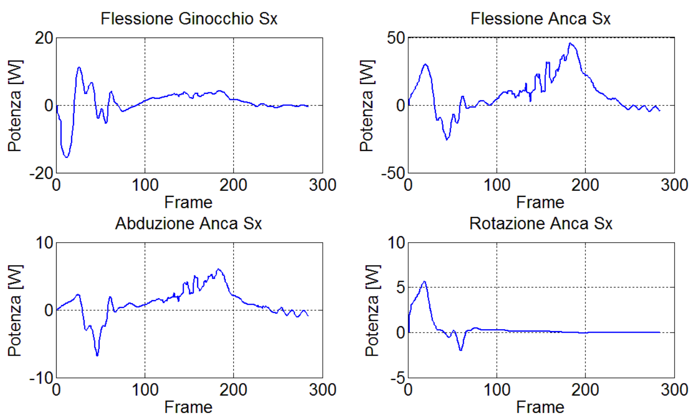


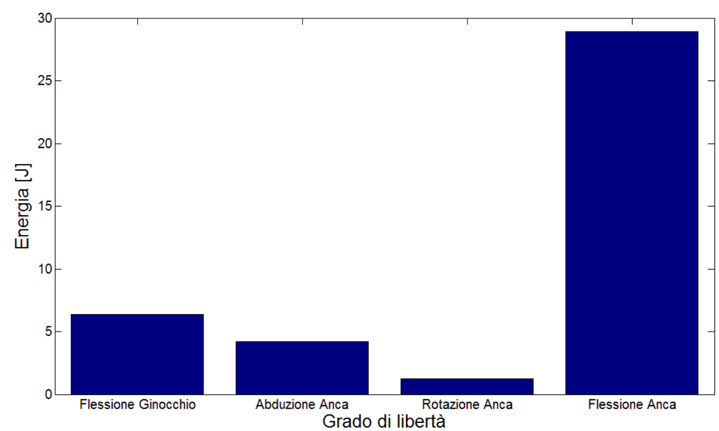
Biomechanical Analysis of the Task

Analysis of torque, velocity, power and energy by task









Biomechanical Analysis of the Task

- Analysis of torque, velocity, power and energy by task